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Oversnow Transport

U. S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

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by Malcolm Mellor

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Hanover, New Hampshire

PREFACE

This monograph summarizes the present state of the art of oversnow transport: study and research have not yet produced a satisfactory theory but current ideas have been included for completeness of treatment.

The paper has been reviewed and approved for publication by the Commander, U. S. Army Materiel Command.

W. L. NUNGESSER
Colonel, CE
Commanding
USA CRREL

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EDITOR'S FOREWORD

"Cold Regions Science and Engineering" consists of a series of monographs summarizing existing knowledge and providing references for the use of professional engineers responsible for design and construction in Cold Regions, defined as those areas of the earth where frost is an essential consideration in engineering.

Sections of the work are being published as they become ready, not necessarily in numerical order, but fitting into this plan:

I. Environment
  - A. General
    1. Geology and Physiography
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F. J. SANGER

OVERSNOW TRANSPORT

by

Malcolm Mellor

THE GENERAL PROBLEM

Present military concepts call for highly mobile units capable of rapid dispersal and efficient movement across country where no roads exist, and many current civilian engineering tasks require movement of men and materials long distances over roadless terrain. Oversnow transport is a particular aspect of the general problem of cross-country mobility, but the characteristics of snow-covered regions are such that special techniques and equipment are required for efficient operation.

The types of snow terrain for which transport capabilities must be developed can be divided into two main categories: (1) seasonal snow covers with an average maximum depth of about 30 in., typifying the sub-arctic and the arctic barrens, and (2) deep permanent snowfields, of the icecap type. If these two classes of snow terrain can be dealt with successfully, most of the earth's snow-covered area is negotiable; only high-mountain snows pose extra problems.

One of the chief problems in oversnow transport is trafficability, by which is meant the ability of the snow to sustain vehicle traffic. Additional problems are raised by the generally severe weather conditions associated with snow country, hazards such as crevasses, thin ice on lake and river crossings, navigation requirements, and big distances between supply and support facilities.

Assuming adequate mechanical efficiency, the performance of a vehicle in a soft terrain is limited by the strength of the material beneath it. The snow a machine runs on must be capable of supporting it without excessive sinkage, and must be able to withstand the tractive thrust of wheels or tracks. The deeper a vehicle sinks, the greater its motion resistance becomes, and consequently the proportion of the total tractive effort available for useful work decreases. This being so, if a vehicle is to travel over virgin snow it must be designed so that it has high flotation (little sinkage) and good traction.

A snow's bearing capacity and resistance to tractive thrust both depend on the shear strength. The shear strength of an undisturbed snow is made up of a cohesive component, resulting from intergranular bonding, and a component of internal friction. Vehicles generally rut the snow they run on, and since the initial collapse of the rutted snow destroys much of the intergranular bonding, the snow beneath the tracks behaves as a predominantly granular material. Shear strength varies from snow to snow as grain size and density vary, and it is influenced directly by weather conditions when changes of temperature and wetness occur.

In order to fully understand the action of vehicles in snow and to formulate sound design criteria, it is necessary to develop a theory which permits quantitative analysis of trafficability problems. Work has been done in this direction, but the theory in its present form is somewhat inadequate, and most commercial oversnow vehicles are designed almost entirely from practical experience. Attempts are being made to evolve analytical methods for critical evaluation of vehicles, performance prediction, and estimation of effects of meteorological, time-dependent, and artificially induced changes in the snow.

For practical purposes, vehicle evaluation is at present made from the results of relatively simple field tests which give drawbar pull as their main indicator. The best practical evaluations are made by observing the operational capabilities of vehicles in various types of snow. The snow testing equipment based on theoretical concepts is complex and it is difficult to sample a snow-covered area adequately using elaborate procedures. On the other hand, simple penetration devices can give some measure of shear strength directly, and their simplicity and speed of operation permits representative sampling of an area by unskilled personnel. By relating the performances of specific vehicles to the penetration resistance of snow, elementary trafficability prediction is made possible.

Oversnow vehicles fall into two categories from an operational point of view: reconnaissance and personnel-carrying vehicles, and freight-hauling vehicles. Personnel vehicles are usually light or medium tractors carrying 1 to 12 men at speeds up to 25 mph; some half-tracked machines with front-end skis are in use, and in favorable situations a few airscrew-driven sleds operate. Most heavy freight is still carried on sleds, which have load capacities from 1 to 20 tons. The most common prime movers are heavy engineer tractors equipped with wide tracks or more extensively modified for low ground pressure. Large-wheel prime movers and trailers are under development, and these may allow the traveling speed of a freight train to be raised appreciably from the present 4 mph or so.

While oversnow vehicles should be capable of traversing virgin snow, they may often follow defined trails "broken" by earlier traffic. These trails can vary from unimproved vehicle tracks to deliberately prepared snow roads. Snow roads are usually confined to areas covered by seasonal snow, although it is possible to process lanes on permanent snowfields to give a high-strength running surface (discussed under "Snow roads and runways" in IIIA-2). Roads of processed snow would only be necessary on icecaps if conventional wheeled vehicles or high-ground-pressure tractors were to be moved.

Vehicles crossing unfamiliar snowfields for the first time face problems of route finding and navigation. These problems are not peculiar to oversnow travel, but the marking of established trails is difficult on icecaps. The frequency of bad visibility necessitates marking at close intervals, and steady accumulation of snow eventually buries the trail markers. Thus the maintenance of markers which allow a trail to be followed in darkness or drifting snow is expensive.

A major hazard on polar snowfields is the occurrence of concealed crevasses, thinly snow-bridged chasms capable of swallowing even the largest tractors. Several methods of crevasse detection have been studied, with varying degrees of success, and it is now possible to locate hidden crevasses quite efficiently using a combination of two or more techniques. When dangerous crevasses are found they are avoided, bridged, or filled with snow.

Ice crossings on rivers and lakes also present problems and dangers (discussed in III-B, "Ice Engineering").

Low temperatures and drifting snow bring additional operating difficulties which are not discussed here but have been covered in technical manuals. They cannot be overlooked, however, since, in the words of a New York Times reporter observing Alaskan maneuvers: "The problems of extreme cold are unending and self-multiplying — the solution of one produces another. Collectively they add up to bulk and weight, which defeat mobility."

Snow terrain

Most of the arctic and subarctic regions of North America and Eurasia are covered by snow for 7 months of the year or more, the snow melting away completely during the summer months. Away from areas of local drifting the average maximum snow depth is about 30 in., and the snow lies on firmly frozen ground. Permanent features of the terrain, such as hills, forests, rivers, and lakes, remain visible throughout the winter.

Over the ice sheets of Greenland and Antarctica (as well as a number of much smaller icecaps in Ellesmere Island, Spitsbergen, Franz Josef Land, Novaya Zemlya, etc.) the snow cover is permanent, except for limited marginal zones. New snow is constantly accumulating on the surface, the older snow being buried and metamorphosed to ice which is slowly discharged to the edges of the ice sheet. For practical trafficability purposes this snow can be considered as limitless in depth. The great depth of snow and ice obliterates all but the largest features of the underlying topography: in the interiors of Greenland and Antarctica the surface is a monotonous unbroken expanse of snow.

The properties of a seasonal snow pack change through the winter as the snow is metamorphosed, but it is generally soft, with density (expressed as specific gravity) in the range 0.1 to 0.3.* The lowest layers, having suffered most grain growth, consist of cohesionless depth hoar which has little strength and can be pushed aside easily when the upper layers collapse under a vehicle track.

Ice-cap snows are generally denser and harder than the seasonal ones, density being in the range 0.3 to 0.4 or more. Density and strength vary to some extent with location; windy areas have hard dense snow, while relatively wind-free areas, such as parts of the Antarctic interior or some ice shelf areas, tend to accumulate soft snow. In Greenland there is some summer melting around the edges of the ice sheet, but in Antarctica melting is rare away from rock exposures. The hard snows found in windy areas give ample support and traction to most oversnow vehicles, but the dunes and sastrugi of the wind-sculptured surface are often big enough to constitute a serious roughness problem. To travel such a region a vehicle must have adequate suspension and freedom from excessive pitching in addition to the usual flotation and traction requirements.

One important difference between seasonal snow and icecap snow is the firm ground surface which underlies the former. For snow covers up to 30 in. (75 cm) deep, most tracked vehicles pick up "ground support" by compressing snow against the unyielding ground. On icecap snows, which are of great depth, this advantage does not exist.

High mountain snowfields pose the most severe mobility problems. In these areas seasonal and perennial snows exist side by side, and new soft snow accumulates to great depths in places. The snow cover is also unstable, being subject to avalanching on steep slopes.

A shallow seasonal snow cover, where snow up to 10 in. (25 cm) deep lies on firm ground, can usually be negotiated by almost any "mud vehicle". This means that, in addition to true oversnow vehicles, jeeps, trucks, farm tractors, construction equipment, and combat vehicles can move freely on reasonably level terrain. Occasional immobilizations of rubber-tired vehicles may result from slipperiness.

In deep seasonal snow, where 10 - 30 in. (25 - 75 cm) lie on firm ground, small wheeled vehicles and agricultural tractors become immobilized. Only tracked vehicles, and special wheeled vehicles having wheel diameters four times as great as the snow depth, are satisfactory. On snow 30 in. deep, small tracked vehicles (gross weight less than 6000 lb) are dependent entirely on the flotation principle, but heavy vehicles are still able to pick up ground reaction and thus are relatively more efficient. Freak vehicles of the Groundhog and Beetle types, which have aggressive open tracks, may actually dig down for ground support without being unduly penalized by high frontal resistance.

Ice cap snows, although very deep, are usually of fairly high surface density, say 0.3 to 0.4 g/cm³. Almost any tracked vehicle can travel over this firm snow, but the less efficient machines may bog down in wind-free regions where soft snow is encountered. In Antarctica, modified farm tractors have travelled to the South Pole, and in Greenland the M48 medium tank has been driven on the ice cap; neither of these machines can be considered an adequate oversnow vehicle, but they illustrate the extremes of the range of vehicles which can cross ice caps.

In areas where very deep soft snow is encountered (depth greater than 30 in., surface density less than 0.25 g/cm³) only vehicles with light track loading and uniform pressure distribution can operate consistently. Deep accumulations and drifts are most common in mountainous terrain, so that vehicles negotiating them should be stable and should maintain their traction and flotation when climbing or sidehilling on steep grades.

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*Snow densities throughout this section are expressed as specific gravities, which are numerically equal to densities given in g/cm³.

Table I

Type of snow terrain		Suitable vehicle types
Shallow seasonal snow cover lying on firm ground. Snow up to 10 in. deep	Flat or small gradients	Tracked LGP* vehicles, wheeled LGP vehicles, high-ground-pressure tracked and wheeled cross-country vehicles (combat vehicles, construction equipment), farm tractors, 4 x 4 and 6 x 6 jeeps and trucks
	Steep grades	Tracked LGP vehicles, wheeled LGP vehicles, high ground pressure tracked and wheeled cross-country vehicles (combat vehicles, construction equipment), farm tractors
Deep seasonal snow cover lying on firm ground. Snow from 10 to 30 in. deep	Flat or small gradients	Tracked LGP vehicles, LGP vehicles with large-diameter wheels, medium ground pressure tracked vehicles with high ground clearance, very large tracked and wheeled vehicles
	Steep grades	Tracked LGP vehicles, special vehicles with large-diameter wheels, some large medium-ground-pressure tracked vehicles
Permanent ice cap snows. Depth is effectively unlimited	Flat or small gradients	Tracked LGP vehicles, LGP vehicles with large-diameter wheels, some medium-ground-pressure tracked vehicles (construction tractors, some combat vehicles)
	Steep grades	Tracked LGP vehicles, LGP vehicles with large-diameter wheels
Very deep seasonal snow. Depth greater than 30 in.	Flat or small gradients	Good tracked LGP vehicles
	Steep grades	High-performance LGP tracked vehicles

*LGP — low ground pressure (up to 4 psi for tracked vehicles)

BASIC THEORETICAL CONSIDERATIONS

The theoretical treatment of vehicle-snow interaction is a special case of the general analysis made for vehicles in soft soils which, in turn, has been developed by adapting conventional soil mechanics theory to the dynamic problems of vehicle trafficability. The following outline, based largely on the work of Bekker and his associates,[1, 2, 4, 13, 30] contains several questionable assumptions and hypotheses, but is representative of current ideas on snow-vehicle mechanics.

Tracked and wheeled vehicles

An adequately powered vehicle can traverse a snowfield if the snow's strength is sufficient to support its weight without excessive sinkage, and also able to resist the horizontal thrust of wheels or tracks. A vehicle usually sinks to some extent, snow compacting in the track ruts until it can develop enough reaction to support the machine.

In sinking, a vehicle improves both the bearing capacity and the shear strength of the snow under its tracks. The increase of shear strength raises the total tractive thrust of the machine, but a portion of this total thrust has to be expended in compacting snow. If sinkage becomes excessive, the thrust expended in compacting snow can equal the total tractive thrust, and the vehicle will be brought to a standstill.

The useful effort of which a vehicle is capable is given by the difference between the maximum attainable tractive effort and the force expended in compacting snow (assuming that the vehicle is not sinking so deeply that it "bulldozes"*):

$$H_d = H_t - H_c \tag{1}$$

where H_d = maximum drawbar pull (an indicator of reserve traction, which may be used for load-pulling or hill climbing)

H_t = maximum tractive effort (the maximum thrust which can be sustained by the snow)

H_c = thrust expended in compacting snow under the track front.

The maximum drawbar pull of a vehicle is generally taken as the principal indicator of that machine's capability under the prevailing conditions. The theory should therefore provide relationships which show how the drawbar pull changes as snow properties change, and also how it responds to changes of such vehicle characteristics as ground pressure and track geometry.

Traction. Since vehicle tractive thrust depends on the shear resistance of the snow, an expression is required to relate shear resistance to snow properties under an appropriate stress condition. In the field of established soil mechanics a similar role is filled by the Coulomb equation, which defines the graphical "envelope of rupture" approximating a common tangent for a family of Mohr stress circles. This is written:

$$s = c + p \tan \phi \tag{2}$$

where

s = shear resistance,

c = apparent cohesion,

p = normal pressure,

ϕ = angle of shearing resistance.

When shear strength of snow is plotted against normal pressure over a wide range of pressures, the resulting graph is not linear, but for the range of pressures and properties applicable to vehicle trafficability work it is assumed that the corresponding

*"Bulldozing" is useless horizontal shearing of snow by a vehicle which is sinking deeply. It represents additional motion resistance, and gives no return in the form of improved traction. In some cases snow may be displaced downward or sideways without useful returns.

section of the curve is sufficiently straight to be represented approximately by the Coulomb equation.* This relationship is therefore adopted[31,32] and rewritten in terms applicable to tracked vehicles as:

$$H_t = bLc + bLp \tan \phi \qquad (3)$$

where H_t = total tractive thrust,

b = total track width,

L = track contact length,

p = vehicle ground pressure.

When a vehicle is traveling at constant forward speed it develops maximum tractive thrust when the tracks are slipping to some extent. This can probably be attributed to a number of things:

(a) Maximum shear resistance is mobilized after the snow has deformed to some extent.

(b) Compressive deformation increases the shear resistance of the snow.

(c) Slip raises the rate of straining, and thereby increases the shear resistance.

(d) By shearing at higher velocity, the track develops more power.

The percentage track slip at which maximum traction is attained is termed the optimum track slip. A typical value for the optimum track slip of an oversnow vehicle might be about 20%. Track slip (or "travel reduction") is given by:

$$\%\ \text{slip} = \left(1 - \frac{V_v}{V_t}\right) \times 100 \qquad (4)$$

where V_v = vehicle velocity (relative to ground).

V_t = track velocity (relative to vehicle).

Figure 1 shows some typical curves relating slip to drawbar pull — commonly termed pull-slip curves. The shape of a pull-slip curve varies with vehicle type and snow type.

The shear resistance parameters $\underline{c}$ and ϕ can be determined from field tests in which known vertical loads are applied to a shearing plate fitted with grousers.† The maximum horizontal force required to deform the snow at a rate of about 5 ft/sec is recorded for a series of tests made with different vertical loads, and the Coulomb line is plotted from the results. Figures 2 and 3 illustrate the method, which is described in detail later. The apparent cohesion of snow results from intergranular bonding, and since this bonding is largely destroyed by the initial impact of a track, the values of $\underline{c}$ are often negligibly small in trafficability studies (i.e., the snow sheared by vehicle tracks behaves as a predominantly granular material).

Sinkage and motion resistance. As a vehicle sinks and makes ruts it uses energy in compacting the snow in the ruts. This energy must be supplied by the driving section of the track (internal resistances and power losses, such as track friction and mechanical inefficiency, are not considered here, since they only increase the power demand on the engine).

As the leading track pads of a moving vehicle descend into the snow they exert radial and tangential forces on the snow, with the net result that the snow is compressed vertically to a depth $\underline{z}_0$ (the rut depth). When the vehicle moves forward a horizontal distance

*Since snow is highly compressible, this is a questionable assumption.

† In general, in situ shear tests give somewhat different results than triaxial or direct shear tests made in the laboratory.

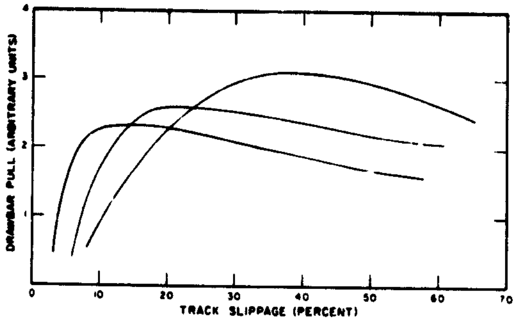

Figure 1. Typical pull-slip curves for a tracked vehicle in different types of snow. Note that some track slip occurs before the vehicle is able to propel itself.

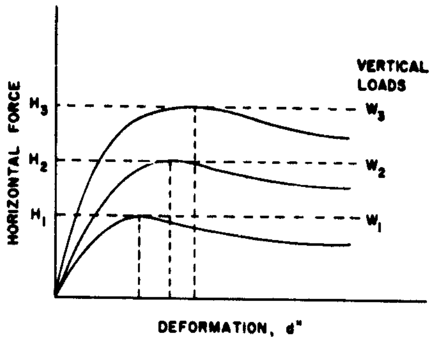

Figure 2. Plot of horizontal shear force against snow deformation for three different vertical loads. Maximum values of shear force from each curve are used to plot shear stress against vertical stress (Fig. 3). (After Vincent, ref. 30)

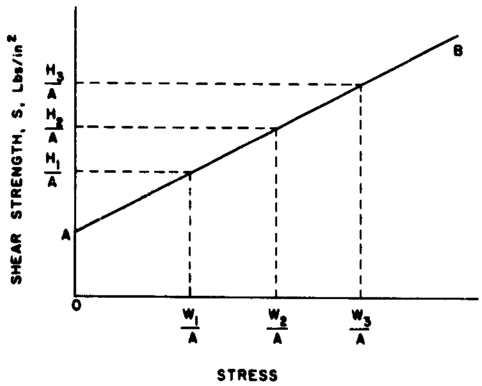

Figure 3. Maximum shear force values from Figure 2 curves and the corresponding vertical loads are divided by the bearing area to convert to stress, then plotted against each other to give the Coulomb line. (ibid.)

h, the energy put into snow compaction is

$$bh \int_0^{z_0} p \, dz$$

where b = total track width,

p = snow reaction (p_0 = vehicle ground pressure),

z = sinkage,

z_0 = final rut depth.

The mechanism of a track is such that horizontal thrust must be provided by the section lying in the snow in order that force can be applied, via the drive sprocket, to the leading track section. The energy for snow compaction, therefore, must be supplied by the driving section of the track.

In moving the vehicle forward a distance h, the work done by the drive section is

$$hH_c$$

where H_c is the horizontal thrust required to energize the compacting section of the track.

If energy losses are ignored, an expression for the thrust required for snow compaction can now be obtained:

$$H_c = b \int_0^{z_0} p \, dz. \tag{5}$$

To evaluate eq 5, a relationship between pressure and sinkage is required. It is found that the results of experiments in which small pressures are applied to a natural snow pack can be adequately approximated by a simple power law:*

$$p = kz^n \tag{6}$$

where p = pressure

k = modulus of deformation (varying with snow type and size and shape of bearing area)

z = sinkage depth

n = an exponent depending on snow properties.

Eq 6 can be made more general by expressing k in a form which makes it independent of track geometry, so that both the modulus and the exponent depend only on snow properties:

$$p = \left(\frac{k_c}{b_1} + k_\phi\right) z^n \tag{7}$$

where k_c = "cohesive" modulus of deformation (curve-fitting parameter),

k_ϕ = "frictional" modulus of deformation (curve-fitting parameter),

b_1 = width of each bearing area (one track on conventional vehicle: $b_1 = \frac{1}{2}b$).

* This equation (first suggested by Bernstein) for short duration static loading may not be quite realistic for a moving system

Substituting from eq 6 or 7, the expression for H_c becomes:

$$H_c = \frac{kb}{1+n} z_0^{1+n}$$

or, (8)

$$H_c = \frac{(k_c + b_1 k_\phi)}{1+n} \left(\frac{b}{b_1}\right) z_0^{1+n}.$$

It should be noted again that this is the minimum thrust required to compensate for sinkage; the "bulldozing" of a deeply sinking vehicle involves additional external resistance.

The cohesive and frictional moduli of eq 7 can be determined for a particular snow in the following way. By loading two plates of width b_1 and b_2 and recording their sinkage, the smoothed curves of Figure 4 are obtained. Plotting log p against log z, the slopes of the resulting straight lines give n, and the values of k_c and k_ϕ can be found from the intercepts on the log p axis (Fig. 5). Test procedures and equipment are described later.

Performance: Taking drawbar pull as the criterion of vehicle performance, the above equations offer a means of anticipating how performance might vary with changes of snow type and vehicle characteristics. Their direct use is limited, however, by the empiricism inherent in their derivation.

If a hypothesis can be developed from the equations, the hypothesis can then be used to design a systematic test program; such testing is more likely to yield productive results than the random testing which has been so common in this field. An example is given below.

Effect of ground pressure on drawbar pull.* Since both total traction and compacting thrust (sinkage resistance) depend on track loading, it is legitimate to inquire whether there is an optimum ground pressure at which a vehicle develops maximum drawbar pull.

From eqs 1, 3, 6, 8, drawbar pull can be expressed as the algebraic sum of two functions of ground pressure, assuming that snow type and vehicle geometry are held constant:

$$H_d = H_t - H_c$$

$$= \Big[(bLc) + (bL\tan\phi)\, p\Big] - \left[\left(\frac{b}{(1+n)\, k^{1/n}}\right) p^{\frac{1+n}{n}}\right] \qquad (9)$$

i.e., a straight line and a power law (Fig. 6).

Differentiating with respect to p gives

$$\frac{d(H_d)}{dp} = bL\tan\phi - \frac{b}{nk^{1/n}}\, p^{1/n}$$

so that the optimum ground pressure, for which H_d is a maximum, is given by

$$p_{opt} = k\,(nL\tan\phi)^n. \qquad (10)$$

* Any deficiencies in equations 1-8 must necessarily affect the results of this particular treatment. The method of analysis, however, is generally applicable.

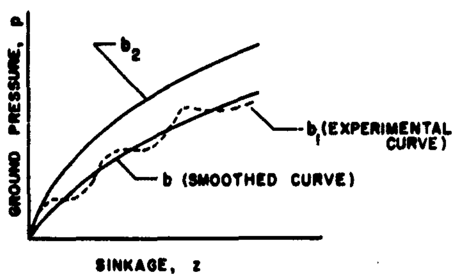

Figure 4. Schematic curves showing the relationship between ground pressure and sinkage for two plates of different sizes. (ibid.)

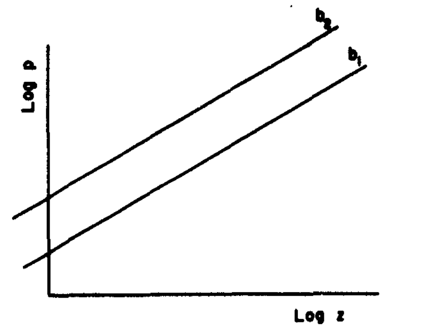

Figure 5. Pressure-sinkage relationships of Figure 4 plotted on logarithmic scales. The intercepts and slopes of the resulting straight lines give the values of $\underline{n}$, k_c and k_ϕ. (ibid)

Note that the optimum pressure is dependent on snow properties (k, n, ϕ) and on the track length.

Eq 9 can also give the immobilization pressure — the maximum track loading for movement in a given snow. The condition is that $\underline{H}_d$ is zero, and therefore:

$$\left(\frac{1}{(1+n)k^{1/n}}\right) p^{\frac{1+n}{n}} - (L\tan\phi)\, p - Lc = 0.$$

The immobilization pressure is thus dependent on snow properties and track length. For a specific problem the above equation need not be solved, as the immobilization pressure is given by the intersection of the $\underline{H}_t$ and $\underline{H}_c$ lines on a plot against pressure (Fig. 6).

Some investigators have sought to find an optimum pressure for which drawbar coefficient is a maximum, tacitly assuming that this pressure would be independent of snow properties and vehicle geometry. Drawbar coefficient is

$$C_d = \frac{H_d}{bLp}$$

and manipulation of this expression shows that there is no maximum for positive values of $\underline{p}$. Figure 6 shows that drawbar coefficient decreases as ground pressure increases.

Figure 6 shows graphically how eq 9 gives optimum pressure, immobilization pressure, and the relation between drawbar coefficient and pressure. The values taken for the two cases are given below.

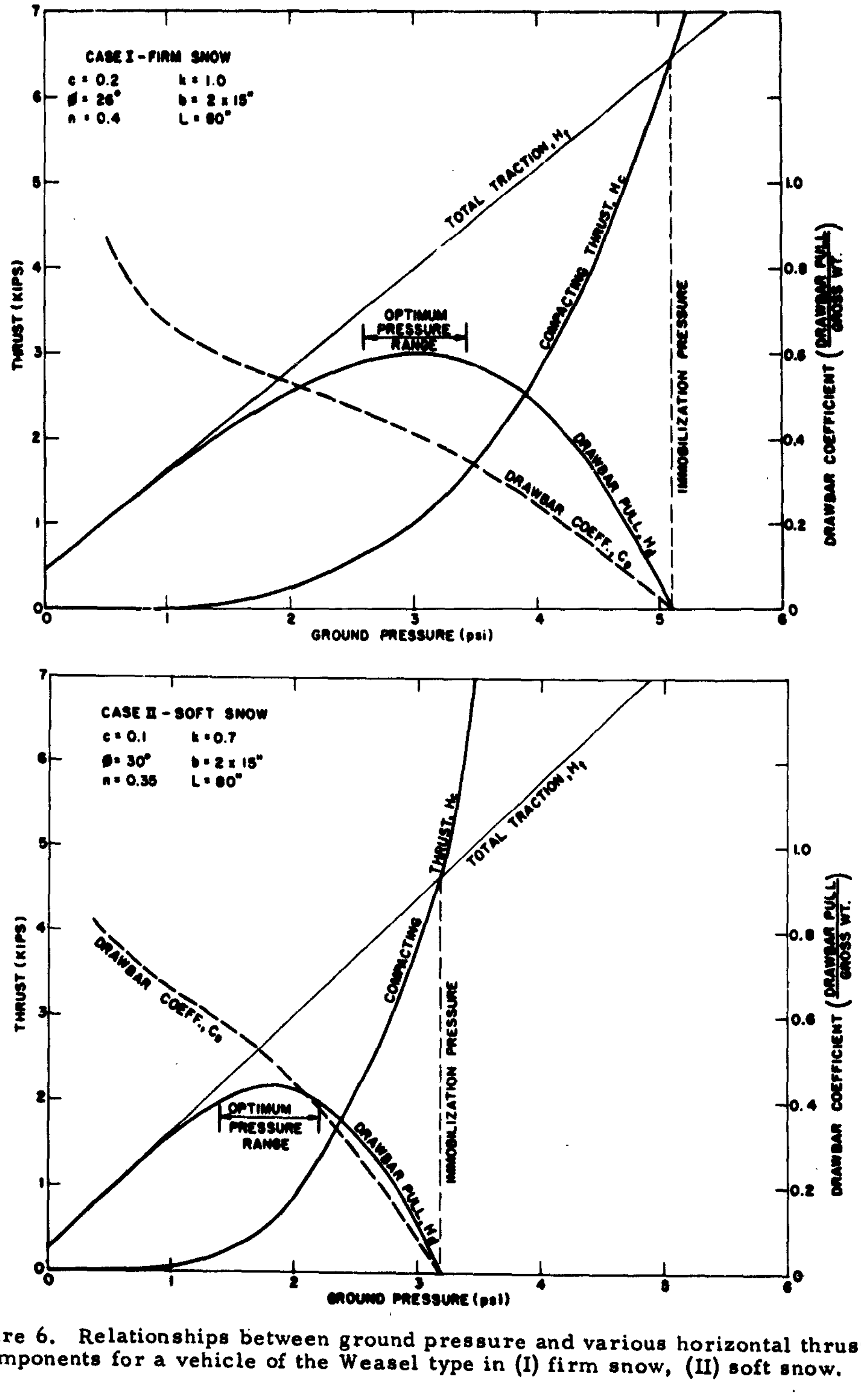

Figure 6. Relationships between ground pressure and various horizontal thrust components for a vehicle of the Weasel type in (I) firm snow, (II) soft snow.

Case I: firm snow — Weasel-type vehicle with two tracks

$b = 2 \times 15 = 30$ in.	$L = 80$ in.	$c = 0.2$ psi
$\phi = 26°$	$k = 1.0$	$n = 0.40$

Optimum ground pressure (maximum H_d): $p_{opt} = 3.0$ psi

Immobilization pressure (H_d zero): $p_i = 5.1$ psi

Optimum drawbar coefficient (C_d at p_{opt}): $C_{d(opt)} = 0.42$

Case II: soft snow — Weasel-type vehicle with two tracks

$b = 2 \times 15 = 30$ in.	$L = 80$ in.	$c = 0.1$ psi
$\phi = 30°$	$k = 0.7$	$n = 0.35$

Optimum ground pressure: $p_{opt} = 1.9$ psi

Immobilization pressure: $p_i = 3.2$ psi

Optimum drawbar coefficient: $C_{d(opt)} = 0.51$

The general findings (not the numerical results) given above, though derived from an admittedly deficient theory, do not conflict with practical experience.

Sleds and low-speed ski vehicles

The physics of ski resistance has been studied in some detail by a number of workers, but for consideration of real sleds and ski vehicles a simplified discussion seems preferable.

The resistance of a sled can be discussed under three headings:

(a) Surface friction. Frictional drag on the base of a ski or runner, and edge friction is always present.

(b) Vertical compaction of snow. In compacting snow beneath its runners a sled does work, which gives rise to horizontal drag. In most cases a sled runs in the ruts of its prime mover, so that compaction drag is slight.

(c) Horizontal shearing of snow. When a sled sinks deeply its runner bows may push snow horizontally instead of compressing it all vertically. Frame members, towbars, etc. may also scrape snow along. Such "bulldozing" is indicative of inefficient operation, and is largely unnecessary.

(a) Surface friction. The various factors controlling friction on snow are summarized below.

Material: The friction between snow and a sliding body varies with the facing material of the body. Coefficients of friction between snow and various common materials (woods, metals, plastics) are given in IIIA-1.

Normal pressure: The apparent coefficient of friction may vary with contact pressure. From experiments with steel runners sliding at 8 ft/sec (2.5 m/sec) on snow at the melting point, an increase of coefficient of friction of about 30% was measured as pressure rose from 0 to 11 psi (0 to 0.8 kg/cm^2).

Velocity: At very low speeds (less than 2 mph) coefficient of friction increases as speed falls, but in higher speed ranges there is not much evidence for a relation between speed and friction coefficient.

Runner length: Within certain limits the apparent coefficient of friction decreases as the length of a sliding body increases.

Grain size: The coefficient of friction decreases as the mean grain size of the surface snow increases.

Temperature: The coefficient of friction increases as temperature falls.

Wetness: The coefficient of friction varies with the free water content of the snow. In broad terms, friction is less on moist snow than on dry snow, but when the snow becomes really wet, friction again increases. Water-absorbent runner surfaces show a greater increase of friction on very wet snow than do water-repellent surfaces.

For further details see "Engineering properties of snow" in IIIA-1.

The component of resistance R_f arising from surface friction is

$$R_f = \mu_e \, bLp$$

where μ_e = effective coefficient of friction,

b = total runner width,

L = total runner length,

p = ground pressure of runners.

The product (bLp), the gross weight of the sled, is fixed, so that R_f can be minimized only by influencing μ_e. Of the factors listed above, only material, pressure, and runner length need be considered. Obviously a low-friction plastic such as Teflon is advantageous as a facing material. The effect of pressure is sufficiently uncertain for this factor to be neglected when considering friction, since pressure becomes more important when sinkage (snow compaction) is considered. Experience, both from experiments and from the sport of skiing, has shown long narrow runners to be preferable to short wide ones. When the practical limit of length for a single runner is exceeded the bobsled configuration can be adopted.

(b) Vertical compaction of snow. When skis or runners slide on virgin snow they make ruts and thus induce resistance. This component of resistance due to compaction, R_e, identical to the sinkage resistance of a tracked vehicle and can be expressed by analogy with eq 8:

$$R_c = \frac{kb}{1+n} \, z_0^{\,1+n}$$

where k = modulus of deformation,

n = sinkage exponent,

z_0 = rut depth,

b = total runner width.

It can also be expressed in terms of ground pressure p:

$$R_c = \frac{b}{(1+n)\, k^{1/n}} \, p^{\frac{1+n}{n}}$$

Since R_c is a strong function of contact pressure, self-propelled sleds and ski vehicles should have a light runner loading. With towed sleds which run in the ruts of a prime mover this consideration is not so important, but runner loading should obviously be of the same order as the track loading of the vehicle (in practice a sled's nominal pressure can be a little higher than the prime mover's nominal pressure, since its distribution is more uniform).

R_c is affected by the length/breadth ratio of the runner, and is directly proportional to runner width b. Thus a long narrow runner is preferable to a short wide one (as was the case for R_f).

(c) Horizontal shearing of snow. When a sled sinks deeply it shears the surface snow horizontally instead of compressing it vertically. Surface snow may be sheared and pushed along by runner bows, low frame members, towbars, and other projections. It can also collect on top of runners, in the framework, and even on the deck, so that the sled's gross weight is increased. This "bulldozing" can be almost completely eliminated by care in design of the sled. To keep bulldozing to a minimum the following requirements should be met:

(1) Excessive contact pressures, and therefore deep sinkage, should be avoided.

(2) The bow curvature of a runner should be gentle in order to push the snow with a strong downward component.

(3) The entire runner should have a slight positive angle of attack. This can be achieved by suitable arrangement of load distribution and towing angle, or by suitable choice of pivot point on swivelled runners.

(4) The sled should have high ground clearance and a "clean" underside, i.e., it should be free from low projections.

The merits of various sleds and trailers are usually compared on the basis of their resistance coefficients, defined as:

$$C_r = \frac{R}{W}$$

where C_r = coefficient of resistance,
R = towing resistance,
W = gross weight.

Since this could be misleading for practical purposes, the ratio of payload to gross weight should also be considered:

$$F_p = \frac{W_p}{W}$$

where F_p = payload factor,
W_p = payload,
W = gross weight.

Thus a more meaningful appraisal factor F_A can be made by combining the resistance coefficient and the payload factor to give the payload per unit drawbar pull (of the prime mover):

$$F_A = \frac{W_p}{H_d}$$

$$\left(= \frac{F_p}{C_r} \quad \text{since } H_d = R. \right)$$

TESTING VEHICLES AND SNOW

Vehicle tests

Vehicle tests range from simple trial drives upon a given snow terrain, through successive stages of refinement, to fairly complex test procedures designed to show the significance of various design features and their relation to variable snow properties.

Test drives. Test driving is the time-honored method of appraising a vehicle's capabilities and comparing its merits and shortcomings with those of other vehicles. The observations made are largely qualitative, but with care they can yield valuable information.

The first question to be answered is whether the vehicle can travel over the snow terrain used for the test. If it achieves one-pass movement over virgin snow adequately, it can then be driven back and forth in the same ruts to determine whether multi-pass movement will immobilize it (in most snows the first pass is most critical — succeeding passes become easier).

Another point of interest is the speed at which the vehicle travels over soft snow, and the maximum tolerable speed which can be maintained over rough sastrugi-covered snow without acute passenger discomfort and danger of damage to the vehicle.

The machine's tractive potential can be assessed by determining the maximum negotiable slope. This requires an area where there is a sufficient range of gradients to define the critical slope. Slope-climbing ability gives some measure of the vehicle's towing capacity, although a steeply climbing vehicle is in an unusual trim and the effective redistribution of weight may affect various vehicles in different ways. "Side-hilling" capabilities should also be checked during climbing tests.

If the vehicle is moving easily when lightly laden it can be gradually loaded and overloaded until it is immobilized. The payload factor (payload divided by gross weight) at the mobility limit can then be used for comparisons with other machines.

All of the above test-drive information can be gained without the use of instruments or special equipment. Nevertheless, this information usually provides an adequate operating evaluation of an existing vehicle, and it will serve to reveal for the existing conditions which machines are good and which are bad in a group of rival vehicles.

Quantitative traction tests. Basic traction tests are designed to find the drawbar pull $\underline{H}_d$, the compacting thrust $\underline{H}_c$, and hence the total traction $\underline{H}_t$. Results of the basic tests may be used alone to compare different vehicles in a given snow condition, or to determine the effects of varying such things as contact pressure or track length/breadth ratio on a given vehicle in a given snow condition. Traction data may also be used in conjunction with the results of snow tests to correlate vehicle performance with snow properties.

Drawbar pull is measured by towing a variable load through a dynamometer drawbar at constant forward speed. Simple spring dynamometers may be used, although remote-indicating load cells are preferable. A simple test procedure is given below.

The test vehicle is coupled to the load vehicle through the dynamometer, which is arranged so that frequent readings can be made by the test observer (a load cell can be connected to a recorder to give a continuous trace). The vehicles begin to travel straight and level on a flat snow surface at the test speed, say 4 mph, with the towed load vehicle in neutral gear and brakes off. When speed is steady the dynamometer is read, and the load is then increased slightly by partially applying brakes in the towed vehicle. The driver of the test vehicle uses throttle to regain test speed, and when speed is steady the dynamometer is read again. The procedure is repeated until the test vehicle becomes immobilized. The entire test is then repeated two more times to give a representative average for maximum drawbar pull, $\underline{H}_d$.

Other methods are occasionally used: in the drag test the tracks of the test vehicle are locked and it is dragged over the snow by a vehicle or a winch; in the static test the test vehicle pulls at a cable fixed to a stationary anchor. Both these methods are unsatisfactory and are not recommended.

To measure the motion resistance, the test vehicle is towed through virgin snow while the towing force is read from a dynamometer. The machine is pulled along in neutral gear on a long line hauled by winch or vehicle. This gives the total motion resistance. The test is repeated on a hard unyielding surface to give the internal motion resistance — that portion of the total resistance arising from track friction. The external motion resistance, which is equivalent to the compacting thrust H_c, is the difference between the total and internal resistances. It should be noted that internal resistance only increases power demands on the vehicle's engine, but external resistance has to be overcome by thrust on the snow.

Additional tests. In addition to the basic traction tests, special observations are required when a searching analysis of vehicle performance is planned.

Since drawbar pull varies with track slip, a measurement of slip is often called for. The forward speed of the vehicle is measured by trailing a bicycle wheel with a trip rev-counter, while the track speed is given by a conventional automotive odometer (readings being taken over a measured time interval). Slip is then given by substituting these values in eq 4.

Vehicle sinkage, or rut depth, is related to vehicle contact pressure, track slip, compactive resistance, and snow properties, so that it is often a required measurement. Continuous readings of sinkage can be arranged by fitting the vehicle with an outrigged "float," which rides on the undisturbed surface and actuates a recorder as the vehicle moves relative to the surface. Combinations of floats will give the longitudinal trim of the vehicle.

The assumptions usually made when considering the vertical and horizontal stresses applied to the snow by a track are gross simplifications. Detailed information on actual stresses can be obtained by fitting into the track a special track pad embodying strain gages, which indicate on a recording oscillograph carried in a control vehicle travelling alongside the test vehicle. The CRREL instrumented track pad is described by Lanyon.[13]

When a test vehicle is heavily instrumented it is convenient to have the data fed simultaneously to a multi-channel recorder. The recorder is carried in a control vehicle which is connected to the test vehicle by an "umbilical cord." Such special control vehicles are fitted with loud-hailers for test direction.

Snow testing for trafficability studies

The snow tests made for trafficability purposes can be grouped broadly in two main categories: tests for empirical correlation with vehicle performance, and tests intended for analytical interpretation. Both types of tests have their place; simple field tests yielding an immediate answer are preferable for vehicle operators (particularly in military units), and detailed tests of mechanical properties are necessary for vehicle development.

Empirical tests. The performance of a vehicle depends on the bearing capacity and the shear resistance of the snow, so that a good field test device should give a simple quantitative description of the snow's strength. An ideal device, from the operator's standpoint, would be one which prodded the snow and gave a number — a number which would tell, after reference to correlation charts, what load a given vehicle could carry or what drawbar pull it could develop in that snow.

In pursuing this ideal, many instruments of the penetrometer type have been tested. Examples are the Rammsonde, the Canadian hardness gauge, the Vicksburg cone, the Proctor needle, the A.D.T. penetrometer, and the drop-cone penetrometer. All are described in IIIA-1, under "Site investigation and snow testing." Their relative merits need not be discussed here.

To function satisfactorily a penetrometer must be capable of sampling to a depth of at least 2 ft, since the depth of snow stressed by a vehicle is very roughly proportional to the track width. Its readings should also be reasonably independent of operator technique.

An instrument which meets these requirements is the Vicksburg cone, a penetrometer developed by the Corps of Engineers Waterways Experiment Station. It can be used

for rapid sampling over a wide area, with no necessity for data reduction, and this simplicity makes it attractive for military purposes. A trafficability prediction system, for snow and for soft soils, has been built around the Vicksburg cone for general Army use.

The W.E.S. cone penetrometer (Vicksburg cone):[6, 18] This instrument forms the basis of the Army trafficability tests for both soils and snows, and index readings given by the apparatus have been correlated with the mobility requirements of a wide range of military vehicles. Used in conjunction with the penetrometer is remolding equipment which breaks down the original structure of the snow and compacts it so that further index readings can be obtained for the remolded material (to simulate the effect of multi-pass traffic).

The cone penetrometer consists of a 30° cone of 0.5 in.^{2} base area, an aluminum staff 36 in. long and $\frac{5}{8}$ in. diameter, a proving ring, a micrometer dial, and a handle (Fig. 7). When the cone is forced into the snow, the proving ring is deformed in proportion to the force applied. The force required to move the cone slowly through a given horizontal plane is indicated on the dial inside the ring. This force is considered to be an index of the shearing resistance of the snow and is called the cone index of the snow in the given plane. The range of the dial is 0 to 300; the standard soil proving ring deflects 0.1 in. at 150 lb load, but the special proving ring for snow deflects 0.1 in. at 50 lb load, giving a cone index reading of 100.

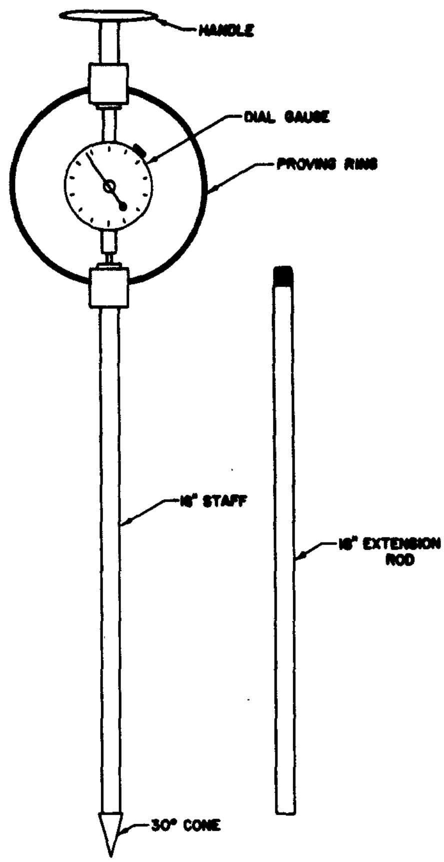

Figure 7. The U. S. Army Waterways Experiment Station cone penetrometer, or Vicksburg cone.

Additional equipment used for remolding tests on snow includes (a) a thin-walled 5,000 cm^3 steel cylinder, 6 in. in diameter and 10.80 in. long, with a detachable 0.25 in. thick baseplate; (b) a 3-lb drop hammer which travels 12 in. on an 18 in. long section of penetrometer staff fitted with a handle at one end and a circular foot 5.5 in. in diameter at the other. The cylinder is driven vertically into virgin snow to collect a sample, the ends are trimmed, and the baseplate is attached. After weighing for density determination, cone index readings are made at the surface of the sample and at 1 in. vertical intervals, using the cone penetrometer. A prescribed number of hammer blows is applied to the snow sample and cone indexes are remeasured at 1 in. vertical intervals in the compacted material.

The tests lead to determination of:

Cone index — the nominal pressure required for penetration of the cone

Remolding index — the ratio of remolded snow strength to original snow strength, based on cone index readings

Rating cone index — the measured cone index multiplied by the remolding index — gives a strength rating for snow subjected to sustained traffic

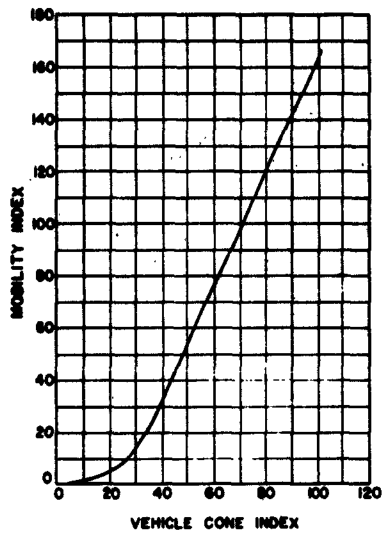

Figure 8. Curve relating mobility index and vehicle cone index in the U. S. Army trafficability system. (After ref. 6)

Vehicle cone index — the minimum rating cone index required for 40 to 50 passes of a particular vehicle.

The above indexes express terrain properties; a further one, the mobility index, is used to express vehicle characteristics.

The method of computing mobility index is given below and its relationship to vehicle cone index is shown graphically in Figure 8.

FORMULAS FOR MOBILITY INDEX IN FINE-GRAINED SOILS*

1. Self-propelled tracked vehicles

$$\text{Mobility index} = \left[\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{track factor} \times \text{grouser factor}} + \text{bogie factor} - \text{clearance factor} \right] \times \text{engine factor} \times \text{transmission factor}$$

where

$$\text{contact pressure factor} = \frac{\text{gross weight in lb}}{\text{area of tracks in contact with ground in sq in.}}$$

weight factor:
less than 50,000 lb = 1.0
50,000 to 69,999 lb = 1.2
70,000 to 99,999 lb = 1.4
100,000 lb or greater = 1.8

$$\text{track factor} = \frac{\text{track width in in.}}{100}$$

grouser factor:
grousers less than 1.5 in. high = 1.0
grousers more than 1.5 in. high = 1.1

$$\text{bogie factor} = \frac{\text{gross weight in lb divided by 10}}{(\text{total number of bogies on tracks in contact with ground}) \times (\text{area of 1 track show in sq in.})}$$

*From TB ENG 37 "Soils Trafficability" (ref. 6)

clearance factor = $\frac{\text{clearance in in.}}{10}$

engine factor: 10 or greater hp per ton of vehicle wt = 1.0; less than 10 hp per ton of vehicle wt = 1.05

transmission factor: hydraulic = 1.0; mechanical = 1.05

2. Self-propelled wheeled vehicles a. All-wheel-drive vehicles.

$$\text{Mobility index} = 0.6\left[\left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor} \times \text{grouser factor}} + \text{wheel load} - \text{clearance factor}\right) \times \text{engine factor} \times \text{transmission factor}\right] + 20$$

where

contact pressure factor = $\frac{\text{gross weight in lb}}{\text{tires width x rim diam x no. of tires}}$

weight factor: greater than 35,000 lb = 1.1; 15,000 to 35,000 lb = 1.0; less than 15,000 lb = 0.9

tire factor = $\frac{1.25 \times \text{tire width in in.}}{100}$

grouser factor: with chains = 1.05; without chains = 1.00

wheel load = $\frac{\text{gross weight in kips}}{\text{no. of wheels}}$ (wheels may be single or dual)

clearance factor = $\frac{\text{clearance in in.}}{10}$

engine factor: greater than 10 hp per ton = 1.0; less than 10 hp per ton = 1.05

transmission factor: hydraulic = 1.0; mechanical = 1.05

b. Rear-wheel drive only. If vehicle being considered is not equipped with an all-wheel drive, the cone index is computed according to the formula for all-wheel-drive vehicles, then multiplied by 1.4 to obtain the vehicle cone index.

c. Half-tracked vehicles. The all-wheel-drive formula is used to obtain the vehicle cone index of half-tracked vehicles by assuming that the vehicle has wheels instead of tracks on the rear end, that the wheels are of the same size and have the same load as the front wheels, and using a grouser factor of 1.1 (to account for increased traction provided by the rear tracks).

3. Towed tracked vehicles

$$\text{Mobility index} = \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{track factor}}\right) + \text{bogie factor} - \text{clearance} + 30$$

where

contact pressure factor = $\frac{\text{gross weight in lb}}{\text{area of tracks in contact with ground in sq in.}}$

weight factor: 15,000 lb or greater = 1.0
below 15,000 lb = 0.8

track factor = $\frac{\text{track width in in.}}{100}$

bogie factor = $\frac{\text{gross weight in lb divided by 10}}{\text{(total no. of bogies on track in contact with ground)} \times \text{(area of 1 track shoe in sq in.)}}$

clearance = clearance in in.

4. Towed wheeled vehicles

$$\text{Mobility index} = 0.64 \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor}} \right) + \text{axle load} - \text{clearance} + 10$$

where

contact pressure factor = $\frac{\text{normal tire pressure in lb per sq in.}}{2}$

weight factor:

15,000 lb per axle or greater	= 1.0
12,500 to 14,999 lb	= 0.9
10,000 to 12,499 lb	= 0.8
7,500 to 9,999 lb	= 0.7
less than 7,500 lb	= 0.6

tire factor: single tire = $\frac{\text{width in in.}}{100}$

dual tire = $\frac{1.5 \times \text{width in in.}}{100}$

axle load = $\frac{\text{axle load in lb}}{1000}$

clearance = clearance in in.

For adequate operation over uncompacted snow, only vehicles with mobility indexes less than about 60 are worth considering. Mobility indexes for a few vehicles with oversnow capabilities are given below.

Vehicle	Mobility index	
M29C Weasel	9	Army ratings[6]
M76 Otter	7	
Crawler diesel tractor, 36 to 45 DBHP	32	
Crawler diesel tractor, 46 to 60 DBHP	36	
Crawler diesel tractor, 61 to 90 DBHP	29	
Crawler diesel tractor, 91 to 140 DBHP	37	
Nodwell 3-axle tracked carrier, model RN21	5	Manufacturers' figures
Nodwell 8-axle four-track transporter, RN200	5	

It should be noted that mobility indexes can not be used for comparing the merits of different vehicles in detail.

Testing mechanical properties. In order to analyze vehicle-snow interaction it is necessary to measure the relevant mechanical properties of the snow. Test methods range from instrument measurements of basic strength properties to use of special devices intended to simulate the action of a track in a single movement. The tests described here have been developed to provide data which can be used in conjunction with the theory outlined in the previous section. Other test equipment, such as the Canadian tilting penetrometer,[8] is available, but has not yet been developed to the same extent.

Shear and sinkage tests:[20] The theory relates the various thrust components of a vehicle to vehicle features and snow properties. The thrust components are measured directly by vehicle testing, and instrument tests are required in order to obtain the relevant snow parameters. These are the shear and sinkage parameters c, ϕ, k_c, k_ϕ, and n of eqs 3 and 8.

The parameters c and ϕ are obtained by shearing the snow horizontally under various vertical loads, measuring horizontal deformation d and horizontal shear stress s. The form of the shear meter is shown in Figure 9. The shear head in this version is a horizontal circular plate fitted with radial grousers. Torque is applied at constant angular velocity from a hydraulic motor and is measured by a pair of strain gages. The total angular displacement is measured by a potentiometer geared to the shear head, and the vertical load is held constant during each measurement by means of a hydraulic servovalve.

One set of tests consists of three runs, each under a different vertical load. For each new run the shear plate is placed on fresh undisturbed snow. The results give curves of the type shown in Figure 2. Maximum values of shear stress s are then read from these curves and plotted against the corresponding values of vertical pressure p to give the Coulomb line (eq 2):

$$s = c + p \tan \phi.$$

The intercept and slope of the line give c and $\tan \phi$ respectively.

To obtain values of the sinkage parameters k_c, k_ϕ and n at a given location, sinkage tests are run with two or three bearing plates of different diameters. The equipment is shown in Figure 10. The load plate is depressed vertically at constant speed, and vertical load on the snow is indicated by a strain gage. The position of the plate relative to surface level is given by a potentiometer circuit. The vertical speed control is hydraulic, and strain gages are interchangeable to accomodate different hardness ranges. The measurements recorded are sinkage z, applied pressure p, and plate diameter b.

A set of tests gives pairs of p and z values for each plate diameter, and these results are plotted on logarithmic scales to give a straight line for each plate in accordance with the power law of eq 7. The equation of the lines reads:

$$\log p = n \log z + \log \left(\frac{k_c}{b} + k_\phi\right).$$

From the plots n, k_c and k_ϕ can be found. The usual way of finding k_c and k_ϕ is to plot $\left(\frac{k_c}{b} + k_\phi\right)$ against reciprocals of plate diameter b, so that k_c is the slope of the resulting straight line and k_ϕ the intercept.

Descriptive snow data. In any test program the snow should be described. A description of the snow completes the test record and permits comparison with results of other tests.

The surface features of the snow should be recorded and, in a seasonal snow cover, the snow depth given. Snow depth is very important, particularly if it is shallow. The grain structure, hardness and wetness of the snow can be noted in accordance with the Simplified Field Classification of Natural Snow Types (see "Site investigation and snow testing" in IIIA-1).

The collapse pattern and the deformation zone beneath vehicle ruts can be recorded by photography. A pit or trench is dug across the ruts left by a vehicle, and the transverse wall is "flamed" with a small oil fire. This etches and smokes the snow, making the original structure and the vehicle's stress bulb* clearly visible.

Snow density and temperature should be measured. Density and temperature information is often available for snowfields whose trafficability properties are unknown and,

*Stress bulb is commonly used, somewhat loosely, to denote the volume of snow obviously deformed by the vehicle track.

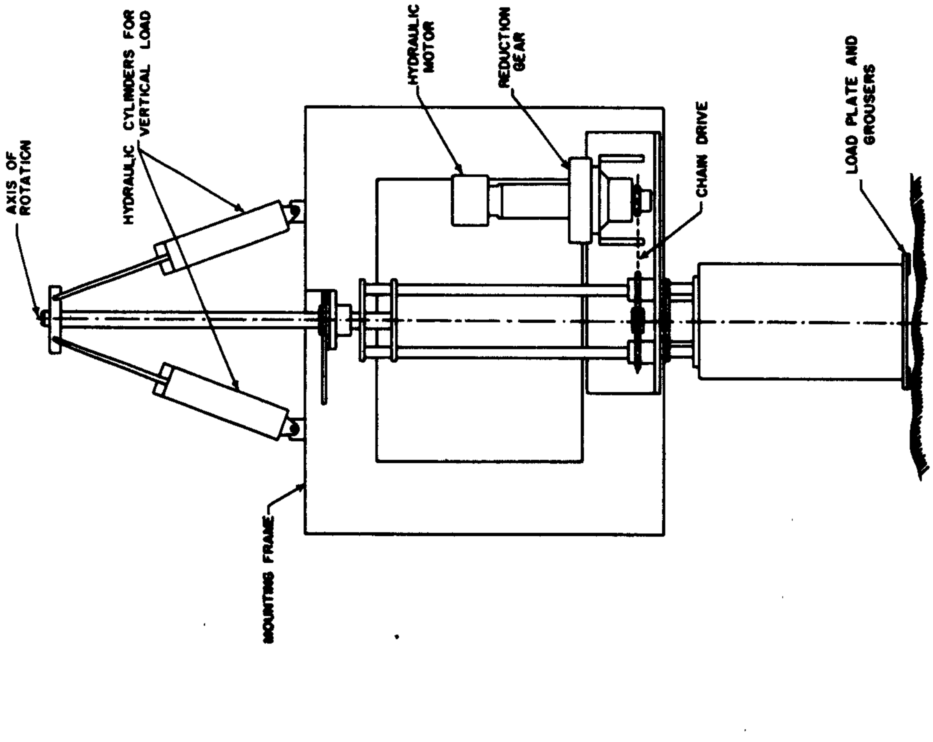

Figure 9. Equipment for determining coefficient of cohesion and angle of friction by shearing snow under various vertical loads. (After ref. 20)

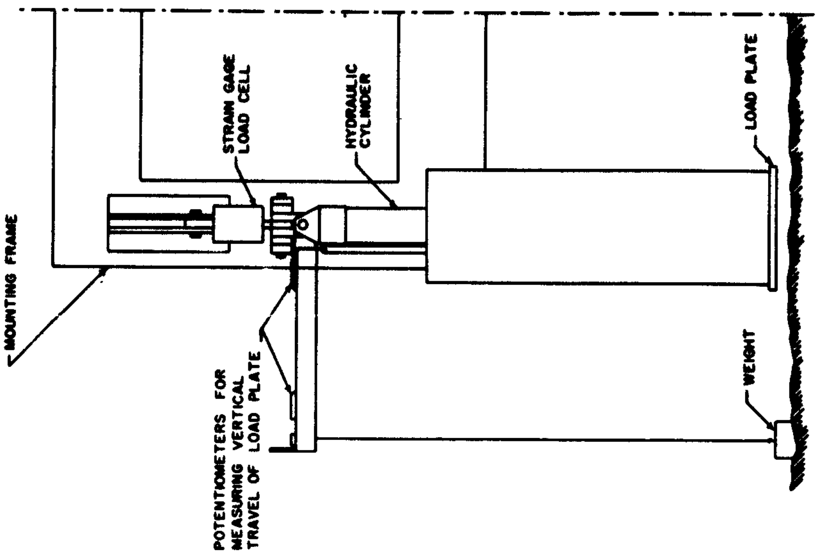

Figure 10. Equipment for measuring pressure-sinkage relationships. (ibid.)

since mechanical properties are influenced by density and temperature, it should eventually be possible to make some prediction of shear and sinkage parameters from a knowledge of density, temperature and grain structure.

At the present time there is no systematic collection of data on shear and sinkage parameters; only scattered and incomplete values are found in the literature. Table II gives some of the reported values.

Testing sleds and trailers

The usual aim in sled and trailer testing is simply to measure the towing resistance of a particular item in a range of snow conditions and at different loadings. This is done by hauling the sled or trailer through a dynamometer towbar, either pulling it through virgin snow on a long line, or towing it in the ruts of the prime mover to simulate normal operating conditions. Results are usually presented by giving resistance coefficients, i.e., towing resistance divided by gross weight. As was mentioned in the previous section, a result of greater practical significance is obtained when the payload factor is divided by the resistance coefficient to give the payload per unit drawbar pull.

In sled testing the frictional resistance can be isolated from the total resistance in this way: The sled is towed through virgin snow to give the total towing resistance; it is then towed through the same tracks a second time to measure the frictional resistance. If sinkage is small, the difference between total and frictional resistances is the compacting resistance.

In trailer testing the total resistance is again given by towing in virgin snow. The frictional resistance is found by towing on a hard surface, and the difference between total and frictional resistances represents the compacting resistance (assuming no bulldozing). In the case of a large-wheel trailer, friction (in the wheel bearings) may be negligible, but a tracked trailer will have appreciable track friction.

For operational testing the sled or trailer must run behind the type of prime mover which will tow it in service.

Table II. Experimental values for various snow parameters.

Apparent cohesion c* (psi)	Apparent angle of friction ϕ* (deg.)	Sinkage exponent n	Sinkage coeff k $(\frac{k_c}{b} + k_\phi)$	Cohesive coeff k_c	Frictional coeff k_ϕ	Temp (C)	Density (g/cm^3)	Worker	Type of test
0.254	21.5							Thomson & Wilson	Analysis of vehicle tests
0.05	30	0.3	2					Nuttall, Wilson & Finelli	" " " "
0-0.47	27-41							Weiss	Mark II soil truss
0.2-0.3								Mark	Shear test
	23-29					0	0.29-0.44	Inaho	Sliding snow on snow
0.9-3.1	21-55					-3	0.31	Diamond and Hansen	Shear vane (Houghton, Mich.)
0.5-1.0	37-53						0.28	" " "	" (comparative)
0.4-0.7	37-45						0.20-0.32	" " "	" (G'land, 200mi E of Thule)
0.5-1.0	36-70						0.35-0.45	" " "	" (G'land, comparative, wet snow near Thule)
1.1	30							Lanyon	Shear vane (Houghton, Mich.)
0.6	29	0.43		4.08	0.78			Weiss, Harrison, Abarca & Bekker	Special instrument (Houghton, Mich.)
		0.6-2.7	0.07-1.91					Harrison	" (Gaspardo)
		1.08		3.70	0.77			"	" "
0.07	22	1.13	0.4	4.6	0.026			"	" "
(0.4?.0.08?)	26-32							Diamond	Vehicle testing
0.12	31	0.36&1.5	0.167&0.5					Thomson	Shear vane
0.3 1.6	25 29	limits for the Greenland snow tested						Wilson, Nuttall & Raimond, Inc.	Shear vane (North Greenland)
0.18	18.3	1.02		3.6	0.3			Harrison & Czako	Special instrument (Houghton, Mich.)
0	21.3	1.24		0.19	0.58			Harrison & Czako	Special instrument (Houghton, Mich.)

*c and ϕ are the parameters relating to shear after initial failure has occurred

APPRAISAL OF EXISTING VEHICLES

Few, if any, of today's oversnow vehicles were scientifically designed. The usual procedure has been to modify old principles in the light of experience. Since this kind of evolution is likely to continue for some time, it is worthwhile to examine the characteristics of existing vehicles in an attempt to find what features distinguish successful vehicles from less successful ones.

Tracked and half-tracked vehicles

In order for a machine to be considered as an oversnow vehicle a number of basic and subsidiary requirements must be met. First and foremost, the vehicle must possess good flotation and traction characteristics if it is to operate on all kinds of snow. It should be capable not only of movement when lightly laden, but should have carrying or pulling capacity. It should also have sufficient power and riding stability to permit reasonable speeds to be attained. The vehicle should be built to provide comfortable crew accommodation in a cold environment and, in the case of a carrier, to give adequate and convenient space for passengers or cargo. Robust construction and mechanical reliability are highly desirable, since oversnow vehicles work in remote and inhospitable areas. Maneuverability in confined areas is necessary, and overall stability is required of vehicles which have to climb or traverse steep slopes. It is desirable that a vehicle should be able to move over snow-free ground without suffering damage.

Fully tracked machines range from small carriers with gross weights around 1 ton, such as the Tucker Sno-Kitten or the Canadair Rat, to heavy prime movers and carriers with gross weights of 40 tons or more, e.g., Caterpillar LGP D-8 tractor, Russian Kharkovchanka, and U. S. Musk-Ox. For carriers, about 40% of the maximum gross weight is payload, and with prime movers the maximum drawbar pull ranges between 20% and 40% of the vehicle gross weight, in average snow conditions. Operating speeds are mainly in the range 3 to 15 mph, although speeds around 30 mph can be attained by some vehicles on smooth snow. Low-speed vehicles, such as modified engineer tractors, have unit powers of about 10 hp/ton, while high-speed vehicles have about 40 hp/ton.

Half-tracked vehicles generally have rear tracks and front-end skis, although a single track is sometimes placed between full-length skis on motor toboggans. Half-tracks often give a smoother ride than fully tracked vehicles, and this contributes to a reasonably high speed potential. They can be steered by turning the skis instead of breaking traction on one track, and this is advantageous in difficult going. Half-tracks range in size from one-man motor toboggans to 15-passenger snowmobiles. At the lower end of the scale are machines such as the Eliason, Polaris and Bombardier motor toboggans (e.g. Fig. 18), which carry about 300 lb and can exert drawbar pulls of a few hundred pounds. The old M-7 (Allis-Chalmers) snow tractor is a heavier two-man machine, while the four-seat Sno-Cat 423 has a gross weight of $1\text{-}\frac{3}{4}$ tons. At the top of the scale are the Bombardier Snowmobiles carrying 12 and 15 passengers. Carrying and pulling capacities are similar to those of fully tracked machines.

Traction. The simple theory discussed above shows that useful tractive effort, as represented by drawbar pull, is dependent on snow properties, on track pressure, and on track dimensions. Maximum drawbar pull is attained with a ground contact pressure which is a function of snow properties and track length. The conclusion which might be drawn is that a vehicle requires a very light track loading to negotiate deep soft snow, but it will pull better on firm snow if heavily laden. A long narrow track is indicated.

Theory shows total tractive effort ($\underline{H}_t$) to depend on track area and contact pressure, but it does not take grouser features into account. Grousers are thought to be most effective in highly cohesive material and not very valuable in granular material, but over the general range of snows shallow grousers have been found advantageous. Wedge-shaped grousers have been suggested, but they do not seem to improve performance appreciably. It has also been suggested that there should be an optimum spacing for grousers, but vehicle tests indicate that best performance is obtained with a grouser on every track pad. This may be connected with the fact that horizontal stress on and against a track pad increases sharply when it passes a bogey.[14]

Figure 11. M29C Weasel. Originally an amphibious light-cargo carrier operated open or with a canvas canopy, this vehicle has been modified for Greenland work by adding an insulated cabin. (See App. A.)

Figure 12. Polecat articulated 2-unit tracked personnel carrier. Engine and crew are located in the front unit and passengers occupy the rear unit. Note Weasel type tracks and special coupling which steers and transmits drive to the rear tracks. (See App. A.)

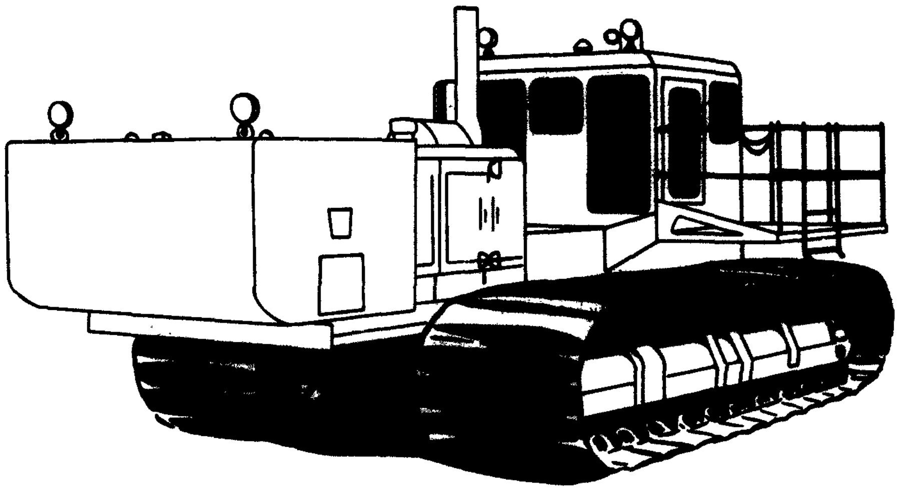

Figure 13. Specially modified Caterpillar tractor used for sled-hauling in Greenland and Antarctica. This machine, the LGP D-8, is a standard prime mover for heavy freight swings. Note the bow fuel tank. (See App. A.)

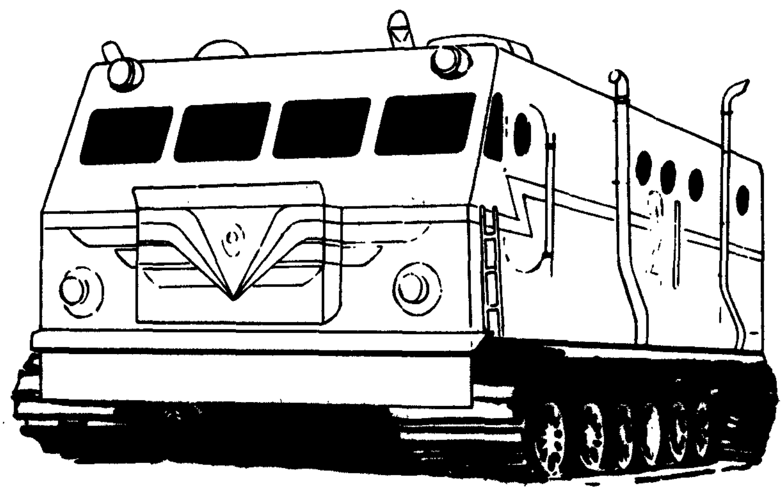

Figure 14. Russian Kharkovchanka tractor. This machine, which has an elaborately equipped cabin, is used for long-distance travel in Antarctica. (See App. A.)

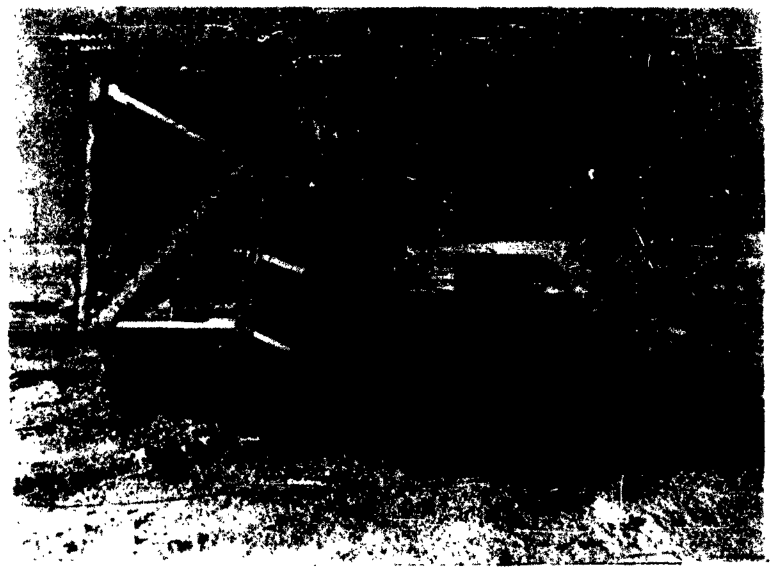

Figure 15. Bombardier Muskeg tractor, Model M-8. Note the flexible tracking formed from rubber belts and steel crosslinks. The tracks of both tractor and trailer run around dual, pneumatic-tired wheels. (See App. A.)

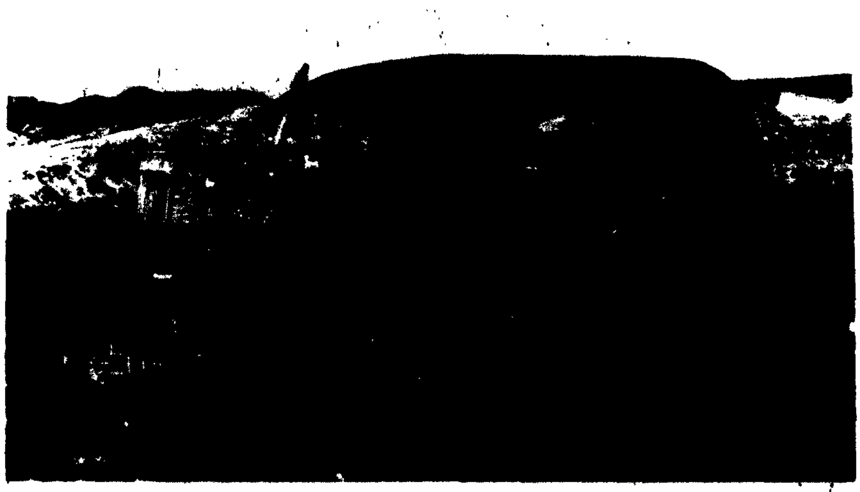

Figure 16. Tucker Sno-Cat, Model 743. Note the pontoons and the open-ladder track. This machine has outstanding performance in deep soft snow. (See App. A.)

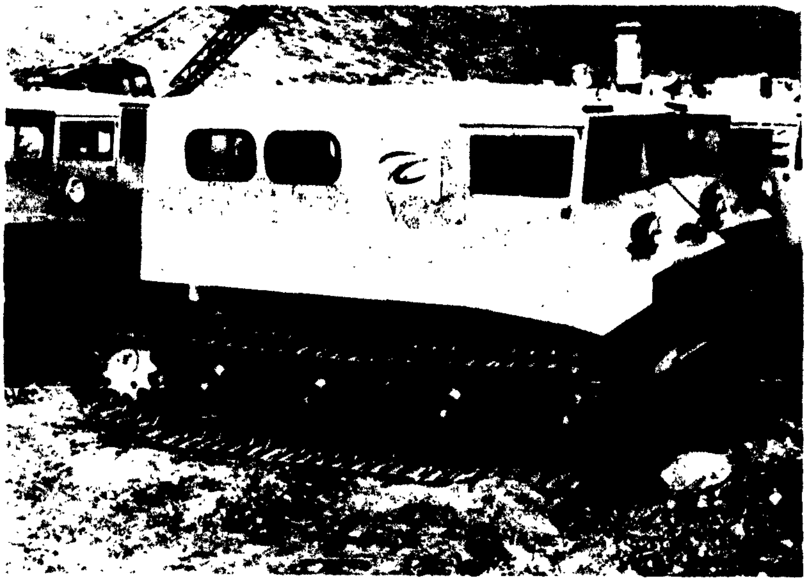

Figure 17. Trackmaster vehicles. Note the very wide flexible tracks. (See App. A.)

Figure 18. Eliason motor toboggan. This machine runs on wooden skis, which swivel for steering. A track running between the skis provides traction. (See App. A.)

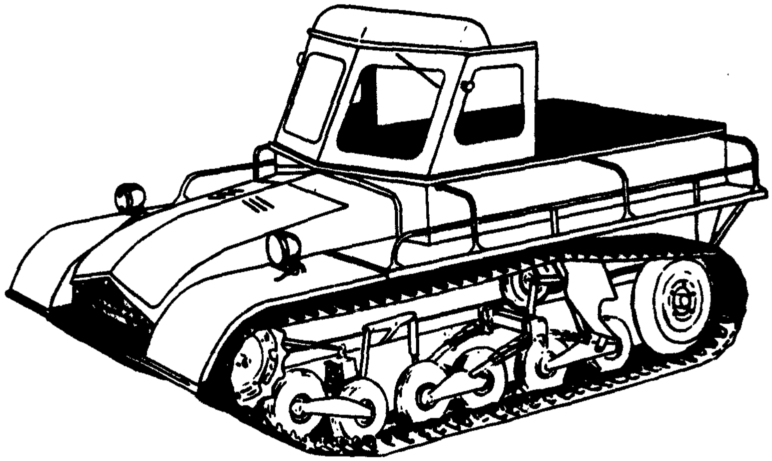

Figure 19. Swedish Snow-Trac light cargo and personnel carrier. (See App. A.)

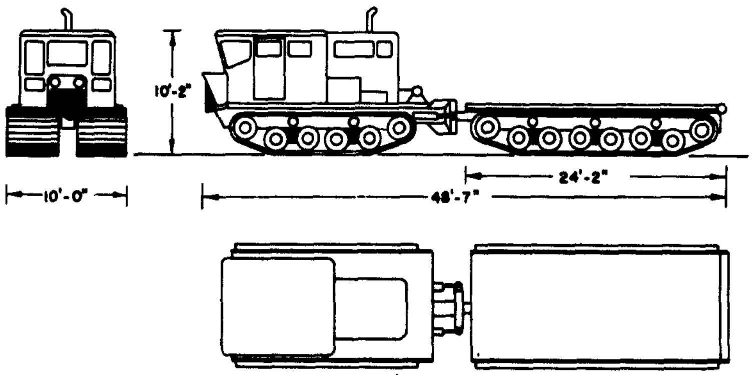

Figure 20. Musk-Ox 2-ton carrier. This heavy articulated freight vehicle was built for travel over the muskeg of Canada. The front elevation illustrates the "bellyless" configuration. (See App. A.)

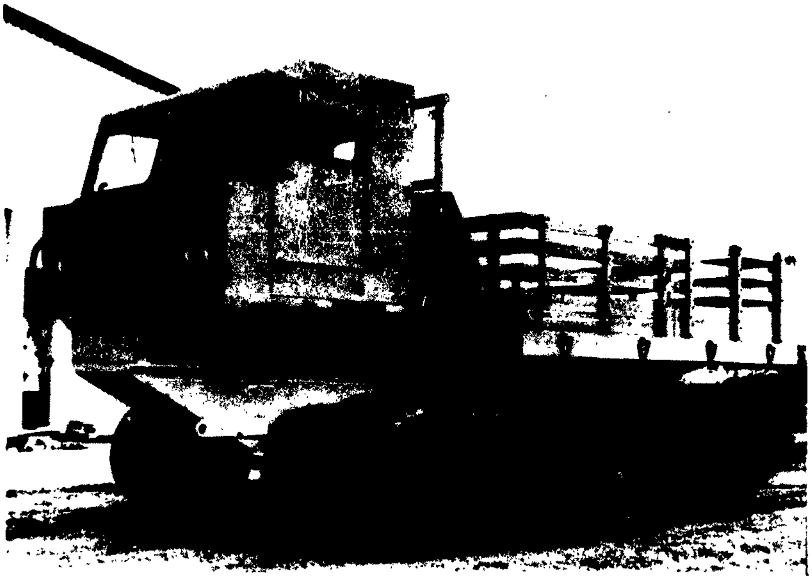

Figure 21. Nodwell tracked carrier, Model RN-140. This soft terrain "truck" has a load capacity of 14,000 lb. (See App. A.)

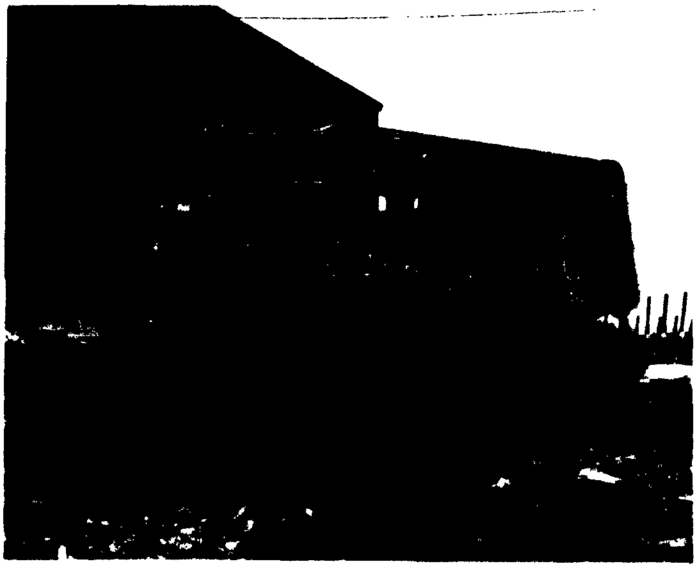

Figure 22. Nodwell tracked carrier, Model RN-110, modified for use in Antarctica. (See App. A.)

Figure 23. Ordnance M76 Otter, an amphibious soft terrain vehicle which has had only limited success in snow. (See App. A.)

Figure 24. Nodwell 4-track articulated freight carrier RN-200. The vehicle has two synchronized engines, one beneath the cab and another at the forward end of the freight deck. (See App. A.)

Tests show that maximum traction is usually obtained with track slips of about 15-30%. This may be attributed to increase of shear resistance with increasing deformation and strain rate, and to increase in the rate of working. It is thought that long tracks give best performance in this respect.

In attempting to develop a large drawbar pull, much depends on what can be done to reduce that fraction of the total thrust which is expended in compacting snow ($\underline{H}_c$). Theory shows this compactive thrust (or sinkage resistance) $\underline{H}_c$ to be directly proportional to track width and proportional to contact pressure raised to a power $\underline{n}$, when $\underline{n}$ is greater than unity. This suggests that tracks should be narrow and lightly loaded.

Figure 25. Ferguson farm tractor with flexible tracking. This vehicle was used on Hillary's pioneer journey to the South Pole and has been used on Vatnajökull. (See App. A.)

The nominal ground pressure of a vehicle is the vehicle weight divided by the bearing area of the track, and this pressure is often quoted as an index of the vehicle's potential for oversnow travel. Since sinkage corresponds more closely to the peak stress than to the mean stress exerted by a track, nominal ground pressure can be a misleading index. The distribution of pressures beneath many types of tracks is far from uniform, and therefore vehicles can sink deeper than might be expected on the assumption of uniform pressure.

The weight of a conventional tracked vehicle is carried on its running wheels, which themselves bear on the section of track laid in the snow. With the vehicle stationary its flexible track is deflected sinusoidally, depression being deepest beneath running wheels and the track arching up in the spaces between wheels. When the vehicle moves the peak stresses pass over all the snow in the path. The outcome is that sinkage is increased and, with a slack track, the wheels are always running uphill on sinusoidally distorted track. Figure 26 shows schematically the stress distributions beneath four common track types.

Transverse track flexure, such as occurs in wide flexible tracks, also produces undesirable stress concentrations.

The pressure distributions in Figure 26 correspond to a situation where the vehicle weight is evenly distributed about the track system. In practice it is not desirable to have a vehicle's center of gravity centrally placed over the tracks because of the tendency to trim in a nose-up attitude due to progressive snow deformation along the track. In addition to compactive sinkage, slip sinkage occurs as snow is mechanically removed at the rear of slipping tracks. Slip sinkage increases with the rate of slip and the prominence of the grousers.

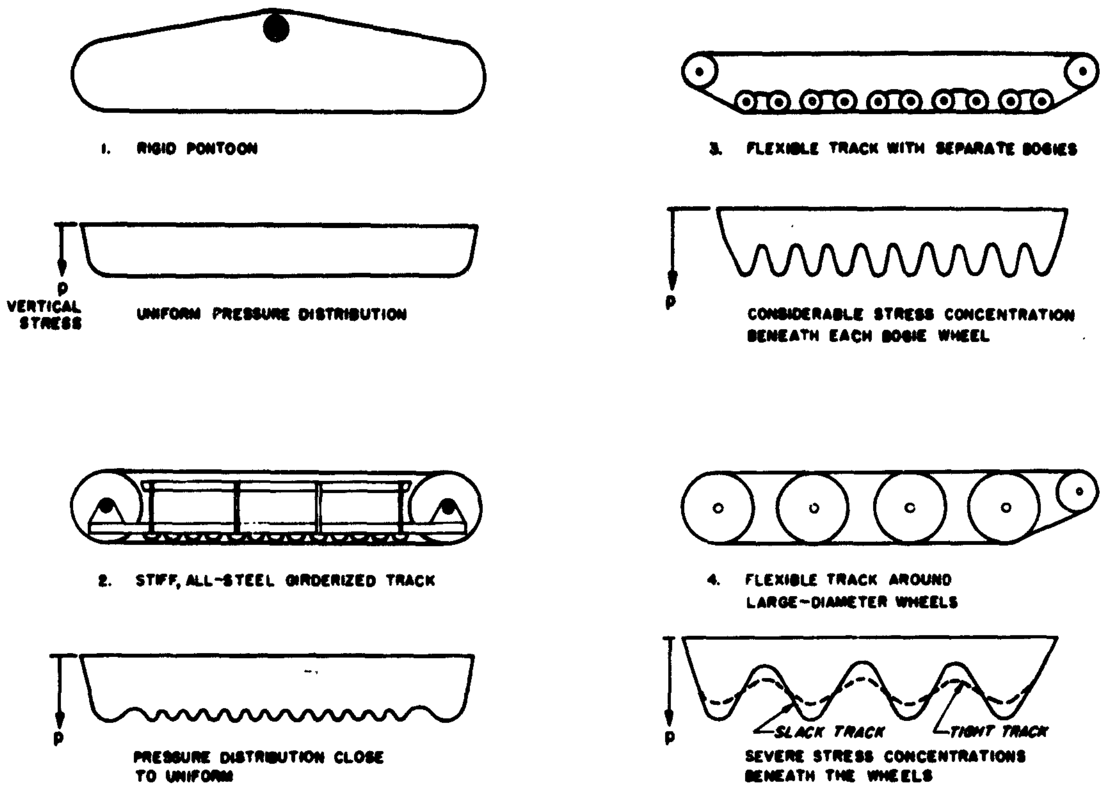

Figure 26. Schematic representation of the stress distributions beneath four common types of track system.

When the sinkage of a track is deep in relation to its vertical dimensions, the track will bulldoze (shear snow horizontally). This is most undesirable and is indicative of inefficient operation. For a track to compact the snow rather than bulldoze it, sinkage must be small relative to the radius of curvature of the track front, i.e., a gentle angle of attack is called for. A circular track front can tolerate comparatively little sinkage before it begins to bulldoze. Bulldozing resistance is proportional to track width, so that it is minimized by a narrow track.

Very deep sinkage allows the underside of the vehicle to scrape the snow, causing additional bulldozing and possibly taking some weight of the tracks. In extreme conditions the vehicle can "hang-up" completely. Resistance is kept to a minimum when bellying occurs by having a smooth projection-free hull and high ground clearance, or it can be eliminated by a "belly-less" configuration (little or no gap between tracks).

In some circumstances it is possible to gain tractive advantage from high track loading without suffering undue penalties from increased sinkage resistance. Large vehicles form stress bulbs which penetrate deep into the snow; this allows them to pick up support from the ground beneath seasonal snow, or from stronger high-density snow in a stratified mass. Figure 27 gives a relationship between the depth of the stress bulb and vehicle gross weight.

The tractive performances of different vehicles are frequently compared by means of the drawbar coefficient, which is obtained by dividing drawbar pull by vehicle gross weight. Drawbar coefficient is a useful dimensionless index for comparing vehicles,

but it cannot be used indiscriminately. Figure 6 illustrates one reason for regarding it with caution: drawbar pull reaches a maximum at a certain track loading, but drawbar coefficient falls as track loading increases. Thus a tracked carrier running on firm snow would develop most drawbar pull when partially or fully loaded, but its drawbar coefficient would be greatest when the vehicle was empty.

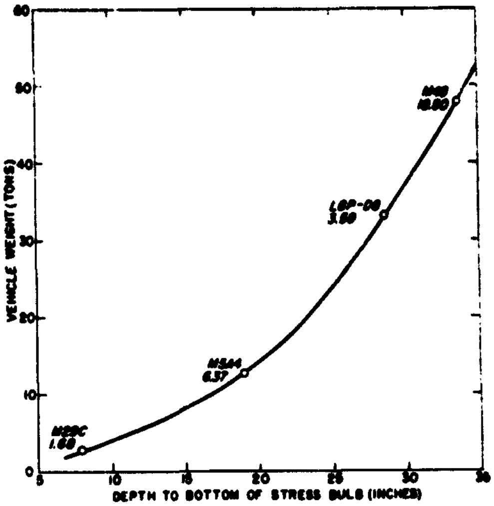

Figure 27. Relationship between vehicle weight and stress bulb depth. The numbers below the vehicle designations are nominal ground pressures. (After Rula, ref. 18)

To sum up, present thinking is that the following features improve tractive performance over deep snow:

1. Low basic ground pressure to permit negotiation of soft snow (drawbar pull can be improved on hard snow by adding payload to increase ground pressure)

2. Even pressure distribution (avoidance of stress concentrations)

3. Long narrow tracks rather than short wide ones

4. Shallow grousers, one for each track joint

5. "Nose-heavy" position for center of gravity

6. Configuration to minimize bellying resistance

7. The "size-effect" favors large vehicles.

These points are discussed in relation to existing vehicles later.

Speed and power. The primary limitation on an oversnow vehicle is traction, but once the vehicle is operating within its tractive capabilities lack of power may limit its speed. If both traction and power are adequate, speed will finally be limited by track mechanism or by rough riding.

For practical evaluation of vehicles, it may be desirable to consider the drawbar power in addition to the drawbar pull. Drawbar power is the product of drawbar pull and vehicle speed.

To develop high drawbar power a vehicle has to meet the following requirements:

1. High drawbar pull (embracing all the requirements listed under the heading of traction)

2. Ample engine power

3. Smooth-riding characteristics.

Existing tractors and half-tracks. Having talked generally about desirable features, we turn to consider the extent to which they are embodied in existing vehicles. (Some of the vehicles now in use are shown in Figures 11-25.)

The vehicles listed in Appendix A have nominal ground pressures up to about 8 psi, but not all of these are true oversnow vehicles in the sense that they can negotiate all types of snow terrain. The machines with nominal pressures above about 5 psi, particularly the military combat vehicles, are suitable only for firm or shallow snows. Vehicles with ground pressures between 2 and 5 psi would generally be capable of travelling over icecaps and over most seasonal snows, but might be limited in their pulling, carrying or climbing capacities. Vehicles with pressures less than 2 psi might be considered for operation over most types of snow, but for work in the most difficult snow

terrains (deep, soft mountain snows) only those machines with pressures of 1 psi or less have demonstrated much capability.

Most of the track types in common use are illustrated diagrammatically in Figure 26, which shows the kind of stress distributions they impose on the snow. The rigid pontoons used on Tucker Sno-Cats (Fig. 16) give a pressure distribution which is very close to uniform. Open ladder-type tracks are used only for tractive thrust, and the unyielding pontoons provide almost ideal support. Caterpillar tractors (Fig. 13) achieve a reasonably uniform contact pressure with their stiff all-steel "girderized" tracks. Rigid track plates are hinged together, and the vehicle weight is carried on front and rear sprockets and on lines of closely-spaced small bogies which are attached to rigid girders. The Weasel-type track (Fig. 11) is more flexible, being made up of pressed steel plates with flexible connections of steel and rubber. The vehicle weight is taken on four transverse leaf springs, which have two pairs of small-diameter dual bogies at each of their ends. The bogies are closely spaced, and drive from a rear sprocket helps to keep the lower half of the track in tension but pressure distribution is not uniform. Peak stresses occur beneath the bogies, although a tight track minimizes this. With highly flexible tracks, in which rubber belts with steel crosslinks run around pneumatic-tires wheels, pressure distribution is far from uniform. The spacing between points of support is greater than wheel diameter, so that large-diameter wheels leave long sections of unrestrained track. This trouble can be overcome partly by overlapping alternate wheels, as was done on the World War II German Tiger tank and on the Otter (Fig. 23). A tight track and rear sprocket drive also help. The tracks of Russian Antarctic vehicles appear to be very slack; while the tracks of mud vehicles may be left slack advantageously to shake cohering mud free, there is no similar benefit in cold snow. Independently sprung bogies introduce further complications into the stress distribution, and also vary track tension as they deflect. The Trackmaster (Fig. 17) has an interesting suspension system which compensates track tension automatically. Transverse track flexure is negligible in stiff steel track pads, but it may be appreciable in rubber belt types, particularly wide ones running around single wheels. Transverse flexure can be limited by using double wheels, as is done on some of the Bombardier vehicles (Fig. 15).

It is now generally accepted that long narrow tracks are preferable to short wide ones of the same bearing area, but traditional steering systems impose a practical limitation on the length of a single track. In the past decade this problem has been overcome on a number of vehicles by using an articulated two-unit configuration (articulation was proposed at the beginning of the century, but was only recently applied). Examples of articulated vehicles are the Canadair Rat, the Bombardier MM freighter, the Polecat (Fig. 12), the Sno-T'rrain, the Wagner Transporter, the Nodwell Transporter (Fig. 24), and the Musk-Ox (Fig. 20). The ratio of track contact length to total track width is in the range 3 to 4 for present articulated vehicles, compared with 1.5 to 2 for single-unit vehicles. Although two-unit articulated vehicles are quite recent, the essential principal has been present in the Tucker Sno-Cat design for many years. The ratio of track length to total width ranges from 3.9 to 4.6 for Sno-Cats.

Virtually all present-day vehicles have closely spaced shallow grousers or cleats. Machines which may have to operate over hard smooth ice may be fitted with additional ice grousers to provide "bite." Ice grousers are relatively narrow and project below the snow grousers; they are well spaced to give high pressures for penetration.

A gently curving track front is advantageous when a vehicle is sinking deeply, but vehicle builders have apparently given this consideration a low priority. Vehicles such as the Weasel, Otter, and Bombardier Muskeg have gentle bow angles, but Sno-Cats, Nodwells, and the Trackmaster have quite an abrupt curvature. Sno-Cats experience so little sinkage that they are probably not troubled by this feature, while in the cases of the Nodwells, the Trackmaster, and similar machines, the advantages of rear sprocket drive perhaps outweigh the disadvantages of a bluff nose.

Most vehicles appear to have a nose-heavy weight distribution when unloaded, but this effect may be cancelled out on a carrier when it is fully loaded. It is sometimes noticeable that an engineer tractor with a blade will trim and pull better than one of the

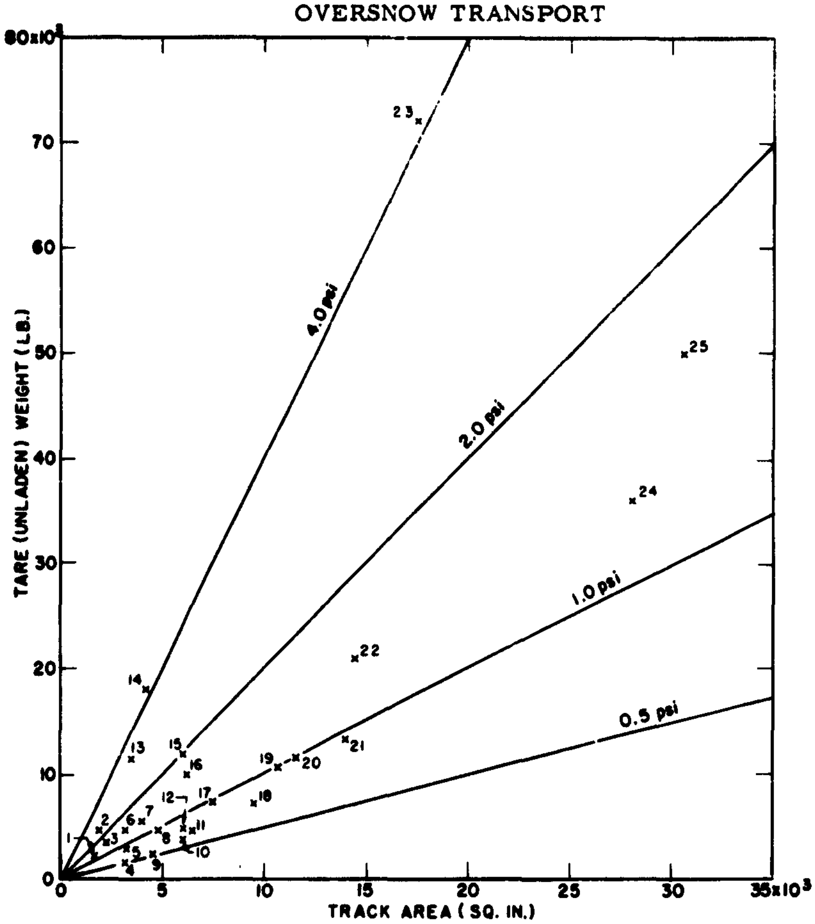

Figure 28. Nominal bearing pressures for unloaded vehicles.

1. Canadair Rat
2. John Deere 420
3. Snow-Trac
4. Sno-Kitten
5. M7 half-track
6. Weasel
7. T-116
8. Nodwell RN21
9. Sno-Cat 423
10. Sno-Cat 443
11. Trackmaster
12. Nodwell RN50
13. Caterpillar D-4
14. Caterpillar D-6
15. Otter
16. Polecat
17. Nodwell RN75
18. Sno-Cat 743
19. Nodwell RN110
20. Bombardier MM
21. Nodwell RN140
22. Sno-Cat 843
23. Caterpillar LGP D-8
24. Nodwell RN200
25. Musk-Ox

same model equipped with a rear winch and no blade. On the Caterpillar LGP D-8 a bow fuel tank counteracts the tendency of the machine to dig in its heels. A sled-towing pintle placed too high applies a couple which pushes down the rear end of the vehicle and thus exaggerates the nose-up tendency.

The ground clearances of most conventional oversnow vehicles are in the range 10 to 20 in. For all but the smallest vehicles, 10-14 in. clearance is rather inadequate, particularly when the underside is not smooth. The "bellyless" configuration avoids the need for high ground clearance by placing the two tracks close together. Examples of bellyless vehicles are the Canadair Rat and the Musk-Ox (Fig. 20).

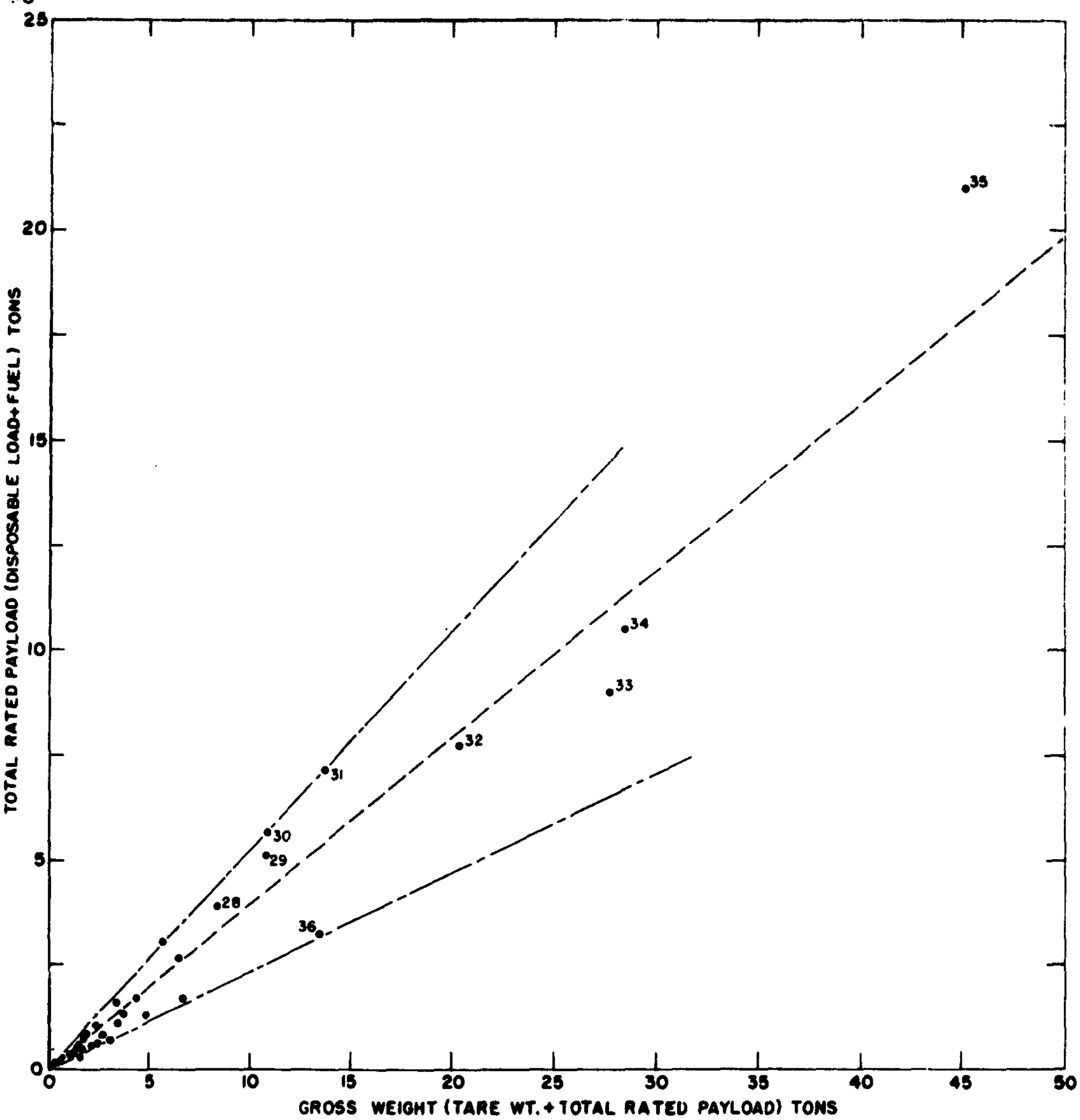

Figure 29. Rated payloads of existing vehicles.
a. Full range (0 to 50 tons)

28. Nodwell RN 75
29. Bombardier Model MM
30. Nodwell RN 110
31. Nodwell RN 140
32. Wagner
33. M8E2
34. Nodwell RN 200
35. Musk-Ox
36. Sno-Cat 843

In considering vehicle payloads it must first be recognized that there is a limit to the track area which can be put on a machine, and also an unavoidable minimum weight in the empty vehicle. These two determine the unladen ground pressure of the tracks, so that the payload will be governed by the maximum permissible ground pressure for the operating environment (assuming structural adequacy of the machine and its suspension). From Figure 28 it can be seen that a few small vehicles have unladen contact pressures as low as 0.5 psi, but a more realistic minimum for small carriers is about

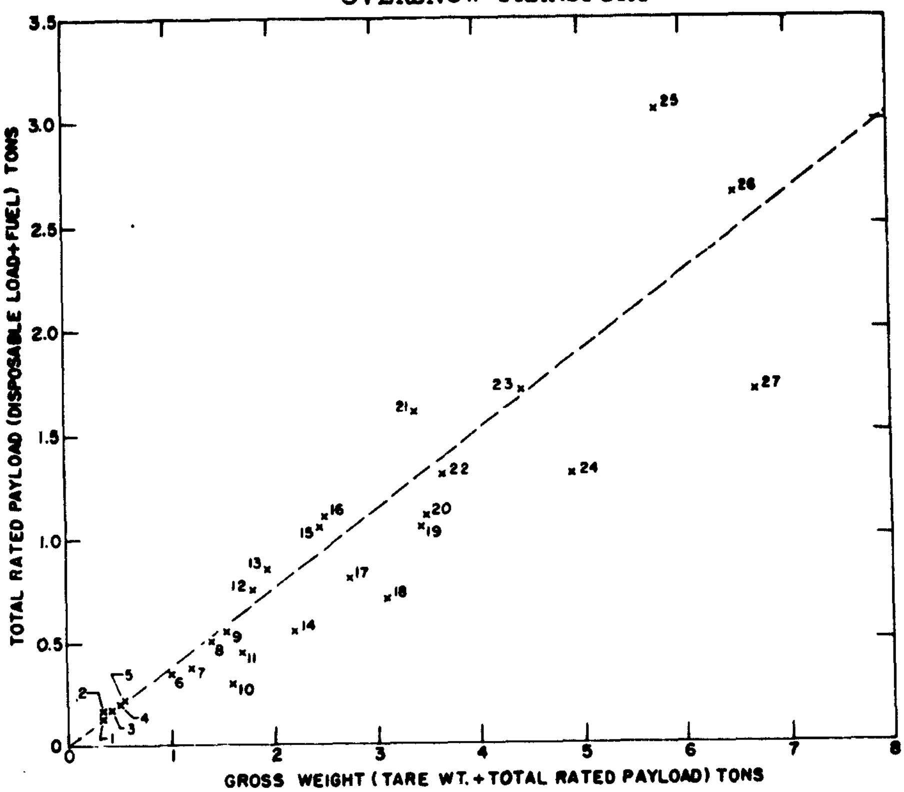

Figure 29b. Enlarged part of low range (0 to 8 tons)

1. Eliason toboggan
2. Ski-Doo toboggan
3. Sno-Traveler K70
4. Sno-Traveler K95
5. Sno-Traveler O13
6. Canadair Rat
7. Sno-Kitten
8. Kristi KT-2A
9. Bombardier BB-60
10. M-7 half-track
11. Sno-Cat 423
12. Kristi KT-3
13. Snow-Trac
14. WNRE Dinah
15. Pack-Rat
16. Kristi KT-4
17. Sno-Cat 443
18. Weasel
19. Trackmaster
20. Nodwell RN21
21. Bombardier Snowmobile
22. Bombardier M-8
23. T-116
24. Sno-Cat 743
25. Bombardier Model S
26. Nodwell RN50
27. Polecat

0.9 psi. The heaviest vehicles are engineer tractors modified as prime movers; they have pressures around 4 psi but, of course, they are not intended to carry a payload other than fuel and driver. Manufacturers usually give a payload rating with a particular snow terrain in mind, which means they differ in their permissible maximum pressures. However, Figure 29 indicates that rated payloads may be expected to be of the order of 40% of the gross weight. Some vehicles have rated payloads as high as 50% of the gross, but these machines cannot operate in deep soft snow when fully loaded. Other vehicles are only rated for payloads running 30% of gross, but this group includes machines such as the Weasel, the Sno-Cats, and the Polecat, which have proven soft snow ability.

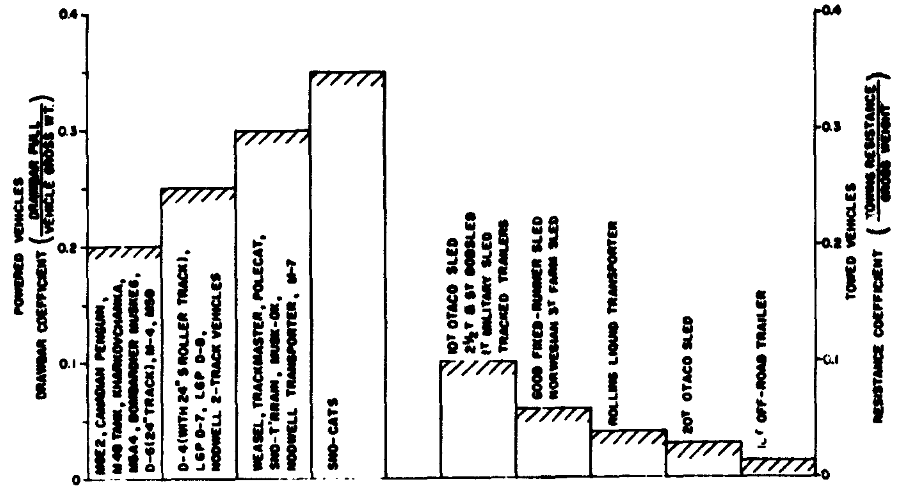

Figure 30. Typical drawbar coefficients for vehicles, sleds and trailers in firm snow (this chart does not indicate relative merits).

Generalizations about comparative pulling powers of different vehicles are apt to be misleading, mainly because of the strong dependence on snow type and the inherent shortcomings of the drawbar coefficient. However, Figure 30 gives some idea of drawbar coefficients commonly found for operation over firm snow. Figure 30 does not indicate relative merit for the vehicles shown.

When a vehicle is running over snow which affords it adequate traction, its speed may be limited by lack of engine power. For example, sled trains hauled by modified engineer tractors often travel at 3 mph because they have insufficient power to engage top gear, which could double their speed. Their problem is aggravated by altitude in Greenland and Antarctica if the engines are not supercharged. Some light carriers also lack power to travel in high gear; they also come to a standstill during a gear change unless the shift is very rapid. Figure 31 shows a fairly wide spread in the unit powers of oversnow vehicles. Three zones have been drawn in, somewhat arbitrarily, to separate groups of vehicles with different characteristics. Zone A includes high-performance vehicles which are usually thought to have adequate power for fast travel; their unit powers are in the range 30 to 55 hp/ton gross. Zone B includes a variety of vehicles which generally might be considered to have powers matching their tractive capabilities, but which could occasionally use more power. Zone C includes the sled-hauling engineer tractors, which were not originally designed as prime movers and might be considered underpowered for that job.

In many icecap regions speed is limited by surface roughness, as the snow is hard and wind-sculptured into dunes and sastrugi. Vehicles pitch and roll badly, causing acute passenger discomfort and structural damage to the vehicle. The two-unit articulated vehicle has an advantage here, as it damps the pitching. The Sno-Cat configuration permits conformance to the terrain. Simple robust construction in the track system helps to minimize vehicle damage in rough terrain; it has been widely found that flexible tracks of the Bombardier, Nodwell and Trackmaster types are more resistant to abuse than, say, Weasel or Sno-Cat track systems.

General sturdiness and simplicity is highly desirable in vehicles which may have to be handled in remote areas by inexperienced operators. Rugged construction often comes at a cost in performance, however. The most robust and reliable machines are the engineer tractors, which will run for months with only routine maintenance, but Figure 28 shows them to have the highest unladen ground pressures. Conversely, the light-treading,

high-performance Sno-Cats require careful operation and maintenance. The Trackmaster appears to be an attempt at an optimum combination of simplicity and performance.

General-purpose vehicles frequently have to move over snow-free ground (camp areas, stream beds, plowed roads, etc.) which may be rocky or muddy. Half-track machines are disqualified on this count if the skis cannot be replaced by wheels. Some track systems, e.g., the Sno-Cat type, are susceptible to damage on rocky ground. Flexible tracks running around pneumatic tires have proved to be very satisfactory on rock and mud.

Insulated, windproof cabins with heaters are a necessity on vehicles operated in the polar regions. The driver's window should be provided with an effective defroster. If operation in crevasse areas is contemplated, seat belts should be fitted and the cabin should have escape hatches. The cabin of a long-range reconnaissance vehicle should be spacious enough to permit sleeping. Examples of thoughtfully designed cabins can be found on the Sno-Cat 843 Antarctic model, the Russian Kharkovchanka (Fig. 14), and the Polecat (Fig. 12).

<u>Wheeled carriers and prime movers</u>

The traction principles discussed for tracked vehicles apply also to wheeled vehicles, i.e., there should be low ground pressure evenly distributed, a long narrow bearing area, and small relative sinkage.

The wheel does not meet these requirements easily: it has little bearing area in comparison with its size, several wheels must be run in train to give a long narrow area, and it can only sink to about one-quarter of its diameter before it begins to bulldoze. On the other hand, the internal friction of a wheel is negligible compared with that of a track, and it has a high speed potential.

Wheeled vehicles in use or under evaluation for snow travel include conventional 4 x 4 and 6 x 6 jeeps and trucks, mud vehicles fitted with large flotation tires, Rolligons, and special vehicles with very large diameter wheels. Some of these are suitable only for use on snow which is either shallow or very hard, and can therefore be eliminated from the present consideration; these are the utilities, trucks and tractors with tires up to about 4 ft in diameter. The Rolligon vehicles, which ride on sausage-like cylindrical bags, can also be dismissed, as the bag diameters are inadequate for operation in deep soft snow.

The only machines which have shown deep snow capability are those which have evolved from marsh buggies and have tires 8 to 10 ft in diameter. Such large diameters appear to be necessary, but they lead to a grotesque vehicle form, causing difficulty in loading and unloading, limiting maneuverability, and prohibiting air-transport.

Perhaps the best-known example of a giant wheeled vehicle was the Snow Cruiser built for Byrd's 1939 Antarctic expedition. This 75,000 lb monster had four 10 ft diameter tires inflated at 15-25 psi. It was a complete failure, bogging down helplessly in the snow of the Ross Ice Shelf.

The most highly developed wheeled vehicle yet tested for icecap travel is the U. S. Army's off-road logistic carrier, or Overland Train. It is a multi-unit freight vehicle with "electric wheels," current being generated in the leading unit and fed to separate motors on all the wheels of the control unit and its trailers. It is believed to have performed well in Greenland, attaining speeds up to 17 mph.

Data sheets for the Overland Train, the Gulf Marsh Buggy, and the Le Tourneau Sno Buggy are included in Appendix A.

The advantages of wheeled vehicles are high speed potential and universal mobility - on the highway and cross country. Their disadvantages are traction limitations and unwieldy vehicle form.

<u>Sleds and trailers</u>

Sleds in use today range from small man-hauled sledges with one or two hundred pound capacity, to heavy cargo sleds carrying 20 tons or more. The smallest sleds are little pulkas (made of fiberglass or aluminum) and toboggans, on which one man can pull camping equipment, tools, etc. Slightly bigger are Nansen sledges and similar types,

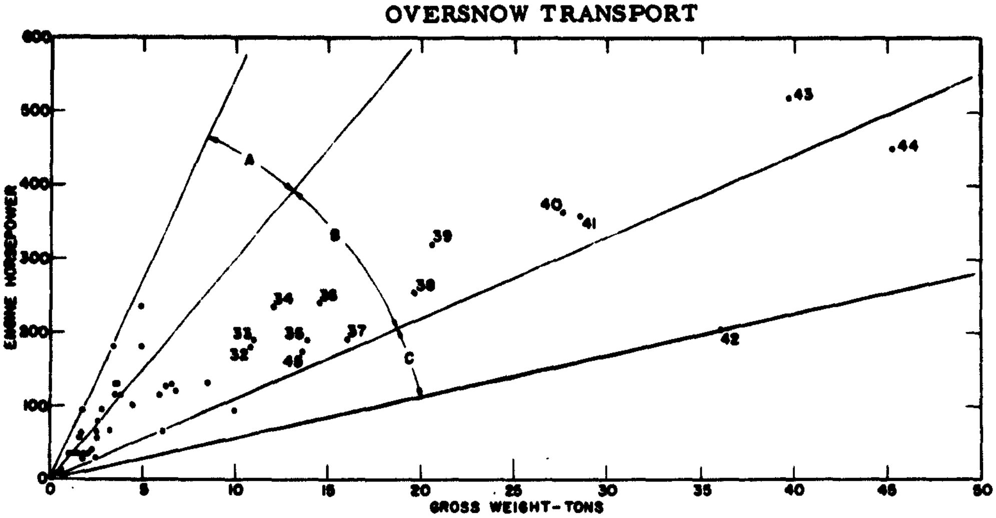

Figure 31. Ratio of engine horsepower to gross weight for existing vehicles.
a. Full range (0 to 50 tons)

32. Bombardier MM
33. Nodwell RN110
34. M5A4
35. Nodwell RN140
36. Pingvin
37. M4
38. M59
39. Wagner
40. M8E2
41. Nodwell RN200
42. LGP D-8
43. Kharkovchanka
44. Musk-Ox
45. Sno-Cat 843

which carry a few hundred pounds and can be hauled by men, dogs, or motor toboggans. Further up the scale are fixed-runner sleds for use behind light tractors, such as the 1-ton M14 sled or the Norwegian 3-ton farm sled. Larger cargo sleds are usually of the bobsled type, which can be obtained in $2\frac{1}{2}$-, 5-, 10- and 20-ton capacities. For heavy freighting, several sleds are linked and towed in trains by tractors, which usually limit their rate of travel to a few miles per hour. In addition to carrying general cargo, sleds mount special equipment for mobile use (drills, generators, workshops, living quarters).

The resistance coefficients (towing resistance divided by gross weight) of many sleds are around 0.1 in typical firm snow, although lower values can be obtained with careful design. Good fixed-runner sleds have resistance coefficients of about 0.6, and the 20-ton Otaco sled has a coefficient of about 0.3 when running behind an LGP D-8 tractor. The ratio of payload to gross weight for freight sleds is about 0.7.

The general principles of sled design were covered under "Basic Theoretical Considerations" and it is necessary to mention only a few practical points here.

Sleds are designed to carry the heaviest load consistent with small sinkage, and ground pressures are generally in the range 3 to 7 psi. Lower pressures are desirable in deep soft snow.

Plastic runner facings lower the frictional resistance; Teflon is favored because of its very low coefficient of friction (0.02-0.04) and its good mechanical properties at low temperature. The Russians also find "fluoroplastic coating" (probably a close relative of Teflon) most suitable. In some circumstances steel runner facings are preferable because of their ability to withstand dragging over rough ice, gravel, and rocks. Some Russian sled runners are sheathed with stainless steel.

Low narrow runners minimize resistance, but because long runners are hard to turn, large cargo sleds are usually of the bobsled type, with two pairs of runners

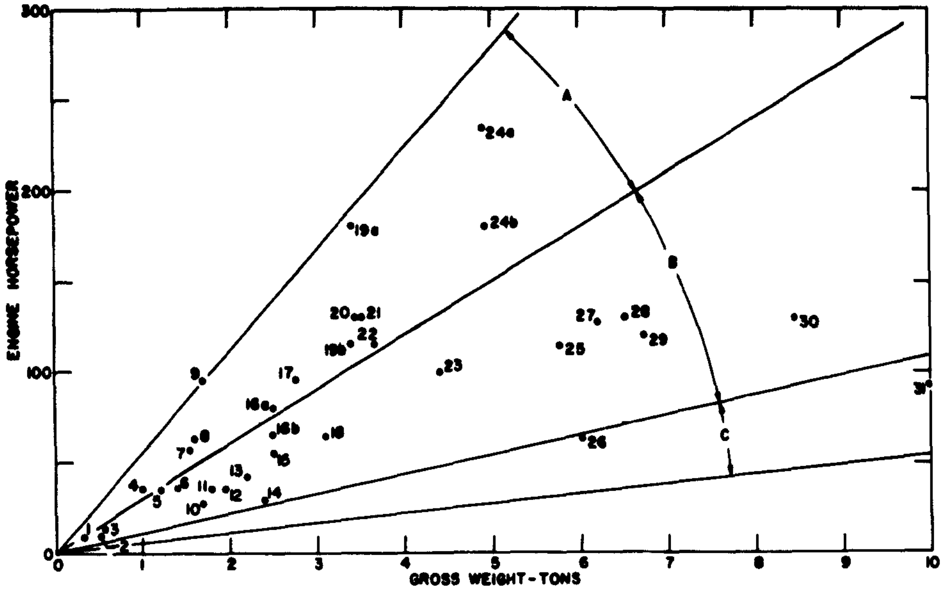

Figure 31b. Enlarged part of low range (0 to 10 tons)

1. Sno-Traveler K-70, Eliason, Ski-Doo
2. Sno-Traveler K-95
3. Sno-Traveler O-13
4. Canadair Rat
5. Sno-Kitten
6. Kristi KT2A
7. Bombardier BB
8. M-7 Half-track
9. Sno-Cat 423
10. Ferguson TE20
11. Kristi KT3
12. Snow-Trac
13. WNRE Dinah
14. John Deere 420
15. Pack Rat
16a., 16b. Kristi KT4
17. Sno-Cat 443
18. Weasel
19a., 19b. Snowmobile
20. Trackmaster
21. Nodwell RN21
22. Bombardier M8
23. T-116
24a., 24b. Sno-Cat 743
25. Bombardier S
26. Caterpillar D-4
27. M-76 Otter
28. Nodwell RN50
29. Polecat
30. Nodwell RN75
31. Caterpillar D-6

swivelling independently about vertical axes (though linked fore and aft with tracking chains). This arrangement permits good steering and tracking and allows conformance to the terrain. The Russians are using long fixed-runner sleds.

For efficient snow compaction, runner bows should curve up gently; a bluff runner bow will bulldoze in soft snow. A sled will compact more efficiently if trimmed with the runners in a slightly nose-high attitude. This can be achieved by loading heavy items well to the rear and making sure the towbar does not pull downward.

Runners with V-shaped cross sections have been found to be advantageous particularly when the sled has to traverse slopes. Flat-faced runners have to be fitted with keel blades to permit sidehilling.

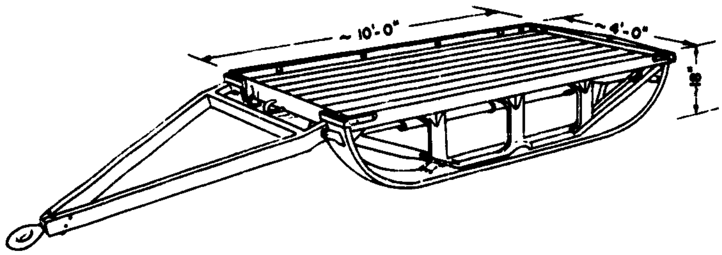

Figure 32a. U. S. military-type light sled, 1-ton.

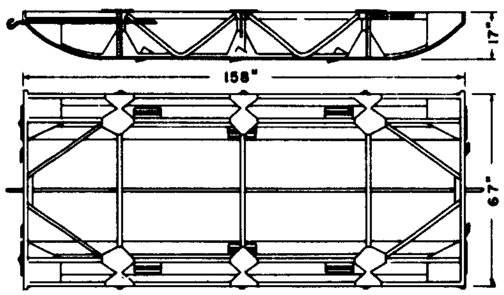

Figure 32b. French light expedition sled, 2-ton, duralumin.

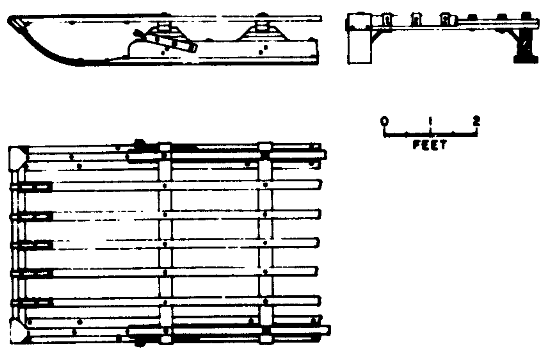

Figure 32c. Norwegian cargo sled, 3-ton.

Figure 32. Small cargo sleds. All are suitable for hauling by light vehicles (see Appendix B).

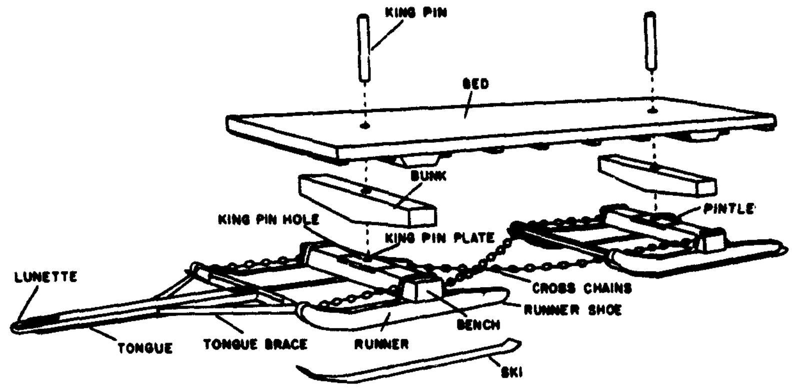

Figure 33. Heavy cargo bobsled. Sleds of this type are available commercially in 5-, 10- and 20-ton capacities (see Appendix B).

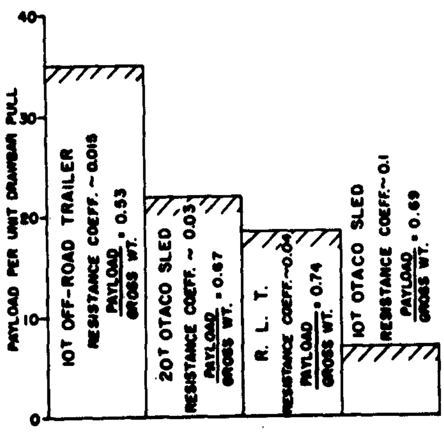

Figure 34. Payload per unit drawbar pull (resistance coefficient x payload factor) for some sleds and trailers.

A sled which is sinking or running in the ruts of a prime mover needs good ground clearance and an underside free from obstructions in order to keep down bulldozing resistance. The towbar of present heavy bobsleds is a bad snow-scraper, but if it were attached higher, say at deck level, it would pull downward when attached to the low towing pintle of an engineer tractor.

Cargo sleds must be very strongly built to withstand the beating and flexing they receive. Most heavy sleds built in North America are constructed largely of wood, but the Russians appear to favor steel and duralumin construction for their cargo sleds.

Freeze-down gives a sled very high frictional resistance on starting, and for this reason experienced sled-train drivers often back down on halting so that slack in the couplings permits the starting jerk to come to one sled at a time. High impulsive loads are thrown on to couplings during jerk-starting, and towbars must be sturdily built to withstand this treatment. The starting problem is aggravated when drift snow accumulates around standing sledges, and some effort should be made to give them a clear starting run by digging out. If freeze-down defies the starting jerks, a wire cable drawn through beneath the runners helps to free them.

Oversnow trailers are of two general types: tracked trailers, on which flexible tracks run around wheels of moderate diameter, and wheeled trailers, which must have large-diameter wheels for consistent operation.

Perhaps the most satisfactory type of tracked trailer is the kind which has rubber belt and steel crosslink tracking running around standard pneumatic-tired roadwheels (Fig. 36). Such trailers can travel over most snow terrains, although their resistance

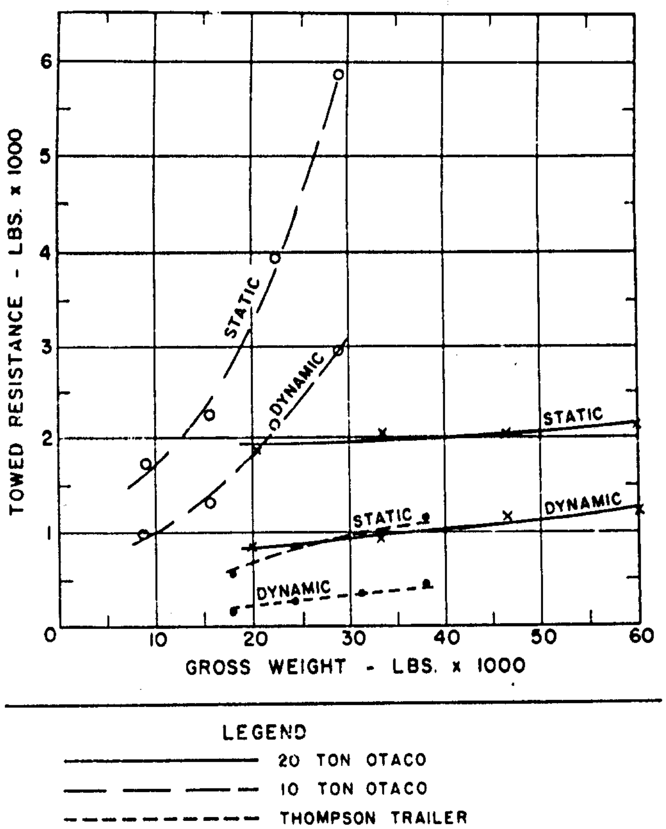

Figure 35. Static and dynamic towing resistances for 10- and 20-ton Otaco sleds and a large-wheel trailer. Tests were performed for U. S. Army Transportation Environmental Operations Group at Site 2, Greenland. The prime mover was an LCP D-8, tests were on moderately dense icecap snow, and air temperature was 32F. (After U. S. Army TRAG, ref. 28).

coefficients are fairly high — about 0.1, or similar to the poorest types of sled. The advantage of a tracked trailer is that it can move over mud and rocks better than a sled, and its tracking can be removed to permit normal highway travel at high speeds. Standard military Athey wagons are unsuitable for oversnow operation, as their ground pressures are relatively high.

Wheeled cargo trailers have been used to some extent, and they appear to be favored for some military purposes. The off-road cargo trailer used by the U. S. Army in Greenland has 12 ft diameter wheels with tires inflated at 15-25 psi. It weighs 9 tons empty, has a payload of 10 tons, and has nearly 200 ft^2 of cargo space. The resistance coefficient of this vehicle is very low under Greenland conditions — about 0.015 — and it has a high speed potential. It does, however, have drawbacks. The huge wheels surrounding the cargo deck make loading awkward and prevent the carrying of bulky oversize loads. Although its resistance coefficient is only half that of an Otaco 20-ton sled, it has a fairly low ratio of payload to gross weight — 0.53 compared with 0.67 for the sled. Nevertheless, its payload per unit pull is 60% higher than that of the sled (Fig. 34).

Another trailer which has proved its worth in recent years is the rolling liquid transporter, which is essentially a pair of broad 64 in. diameter tires filled with fuel. Loaded RLT's have been found to have resistance coefficients of about 0.04 under Greenland conditions, which gives them a favorable payload per unit pull (Fig. 34).

A trailer has been made by joining two RLT's with steel framing and decking. This vehicle, the Rolli-Trailer (Fig. 37),is a combination fuel transporter and dry cargo carrier. It appears to work well on hard snow and shallow snow, but is unlikely to give satisfactory performance in deep soft snow.

Aero-sleds

Under the heading of aero-sleds can be included propeller-driven vehicles mounted on ski-runners, propeller-driven machines with boatlike hulls, and propeller-driven vehicles with submersible hydrofoil-style runners.

Sleds with engines and aircraft-type propellers have been in existence for about fifty years, but they have not been widely used in Western countries. Such machines are capable of traveling across flat smooth snowfields at high speed, which makes them

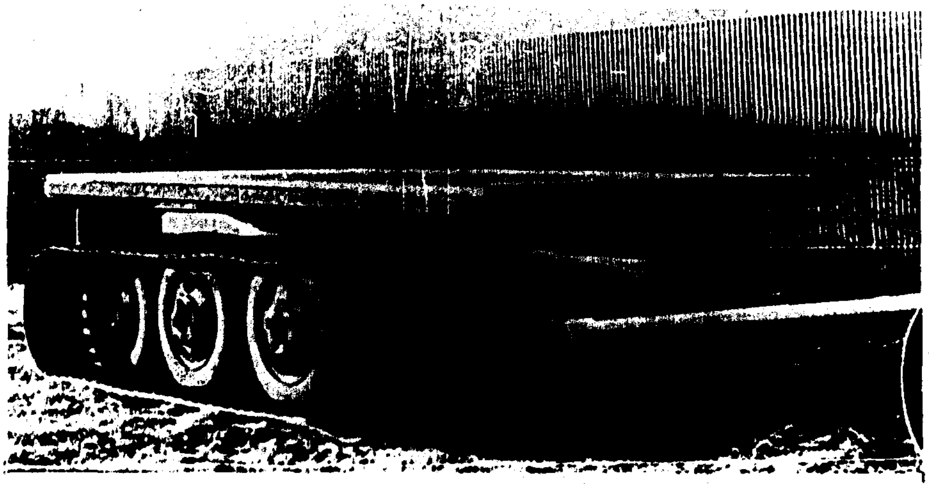

Figure 36. **Robin-Nodwell tracked cargo trailer.** On removal of the flexible tracking it can serve as a normal highway trailer.

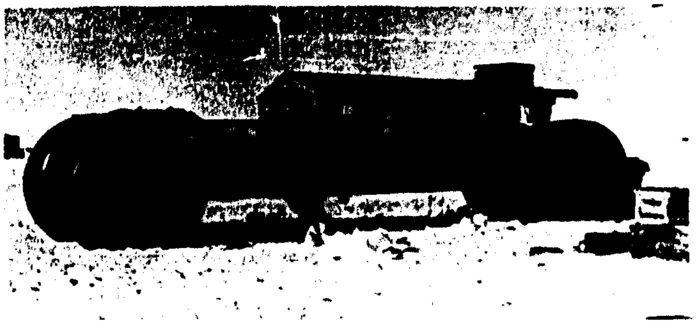

Figure 37a. The Rolli-Trailer, a combination fuel transporter and dry freight carrier (see App. B).

Figure 37b. 10-ton cargo trailer (Thomson trailer) used for freight hauling on the ice cap.

attractive as passenger-carrying vehicles. However, they do not pull well at low speeds and have poor climbing ability, particularly when starting from rest. Passenger-carrying aero-sleds are used regularly on frozen lakes and rivers in Russia, and general-purpose vehicles of this type are believed to be in use on snow-covered tundra and sea ice in the Russian Arctic. In North America small aero-sleds are used by sportsmen, game wardens, and others, but there is little interest in using them for serious oversnow transport purposes.

One problem in the design of aero-sleds is the load distribution on the skis. In addition to the static loading it is necessary to consider the moment introduced by the propeller thrust, the torque reaction, and the centrifugal loadings during high-speed turns. Other problems include general stability, which is more critical at high speed, and shock loadings produced by the skis hitting drifts or patches of bare ground.

Swamp boats with strengthened hulls have been tried for oversnow travel, generally with discouraging results. Steering is difficult at low speed, and braking is a problem.

An interesting new type is CRREL's experimental vehicle, the Keebird, which was designed to test the concept of an undersnow ski operating somewhat like a hydrofoil. The Keebird is driven by a 280-hp aircraft engine turning a shrouded 3-blade propeller. It rides on Teflon-covered aluminum skis, 25' 6" x 6 ", which have a sharp-edged nose instead of a turn-up. The skis can be flexed through servo-hydraulic controls to give steering and rise-and-dive. Its gross weight is about 4,000 lb. The Keebird program has shown that it is feasible to run a ski under the snow to give smoother riding, but a number of technical problems still have to be overcome.

Air cushion vehicles (Ground effect machines)

Air cushion vehicles (ACV's) derive relatively high lift for a given power by operating close to the surface and taking advantage of the ground effect phenomenon. In recent years there has been a surge of interest in their development, and in Britain "second generation" vehicles with commercial possibilities have been produced. Although ACV's have not yet been evaluated for oversnow operations, they are of considerable interest. While an ACV lacks pulling power and climbing ability, it is capable of high speed over soft terrain and moderately rough surfaces, and is less susceptible to crevasse hazards than a tractor. It is not limited by weather as a helicopter, and it is more economical.

Data sheets for a number of U. S. and British ACV's are given in Appendix C. These show that the experimental models tend to be very highly powered while having a hover height which seems too low for cross-country work. More highly developed machines have favorable power/weight ratios and are capable of better hovering heights.

An oversnow ACV should probably hover at about 2 ft above the surface (to avoid sastrugi, ice hummocks, rocks, etc.), be capable of speeds up to 50 mph, have the ability to climb 20% grades, and be stable in windy conditions. Such a vehicle would probably have a peripheral air jet and unit power of over 100 hp/ton gross (which is theoretically excessive). A peripheral skirt would perhaps be advantageous, and it might be possible to use lightly-loaded V-skis (after the style of the Folland GERM) to provide directional control, stability, and sidehilling capabilities.

ACV's cannot climb steep grades in their present form, and they might have trouble in soft snow.

Another application of the air cushion principle is augmentation of flotation tires on wheeled vehicles in very soft conditions. In the U. K. a modified Land-Rover is being developed; it derives additional support from an open-plenum air cushion in soft terrain. In Canada the Avro Company has developed a 2-unit, 4-wheel, articulated vehicle, the Gemini, which also employs the air cushion principle.

TRAIL MARKING AND CREVASSE TECHNIQUES

Trail marking on polar snowfields

Navigation of a vehicle across the featureless expanses of a polar snowfield is in many ways similar to marine navigation, the only visible reference points being celestial bodies (and then only when the sky is clear). Proximity to the poles makes magnetic compasses insensitive, so that gyro compasses become desirable. Like the sea, also, a polar snowfield has its hazards to navigation, concealed crevasses being substituted for reefs and sandbanks. Thus exploratory vehicles must be manned by trained navigators capable of using theodolites, bubble sextants and astro-compasses to determine positions and azimuths, and also experienced in the negotiation of dangerous and difficult terrain. For routine freighting and communication runs between permanent camps, however, it is clearly desirable to free drivers from navigational responsibility and to have safe trails which can be followed easily in any weather conditions and at any time of day or night.

While there are no theoretical difficulties about providing continuous route marking, the steady accumulation of snow on an ice cap necessitates frequent maintenance or replacement of markers, and expense becomes a problem. There are two broad approaches to the question at the present time: the development of traditional systems of visual marking, and the introduction of electronic devices which permit vehicles to be aligned with buried wires, radar targets, radio beams, and so forth.

Visual markers. Since the early days of polar travel, routes have been marked with flags, snow cairns, and jettisoned items, and today similar things are used for trail marking. Some comments are made below.

Flags: The flags used today are fabric pennants about 18 in. long with a 12 in. base, tied to a bamboo or metal stake which is driven into the snow by hand or set in an augered hole. Bamboo poles with butt diameters of 1 - 2 in. and 12 - 16 ft long have been found most efficient and economical in Greenland. A flag is too small to be seen clearly from more than a few hundred yards, and the distance from which it is visible varies considerably with lighting conditions and the nature of the snow surface which forms a background. In bright sunlight pennants are difficult to see against a sastrugi-covered snow surface because of the over-all stippling of light and shadow. The area exposed to an observer varies with the wind direction, and a flag blowing towards, or away from, an approaching driver is a poor visual target. Pennants of cotton fabric fray rapidly in sustained high winds and may be reduced to a mere shred after severe storms. Nylon and similar fabrics have only slightly longer life. The color of marker pennants affects their visibility to some extent, but color is not of prime importance. In ablation zones marker flags often fall in summer owing to melting of ice. This difficulty is usually avoidable; light stakes remain stable if planted 6 ft or so beneath the surface.

Flags are relatively cheap, light to carry, and easy to place. They are highly satisfactory for detailed route marking through crevasse areas and are adequate for general trail marking if placed close together. Spacing of 200 - 300 yards has been found ample in Greenland, with quarter-mile spacing on infrequently-traveled trails. The azimuths of the trail legs should be recorded to facilitate trail-following.

Reflectors: On trails which have to be traveled in darkness it is helpful to attach reflectors to the flagged stakes which act as daylight markers, so that they can be be picked up more easily by vehicle headlights. Three-inch diameter glass or plastic reflectors (red or amber) on metal backing plates are used in Greenland. These not only reflect headlights but also give good radar reflections. One snag is that the reflectors sometimes become coated with blown snow or hoarfrost.

Cairns: Snow cairns were commonly used as route markers in the days of dog-sledging, when weight and space on the sledges were limited. The usual technique was to cut snow blocks with a spade and stack them in pyramidal form. Nowadays a 10-ft cairn can be pushed up without much trouble by a bulldozer. With reasonable lighting conditions a big cairn stands out well on an otherwise featureless snowfield, and its "shine or shadow" can often be seen a mile away. In whiteout a cairn is invisible unless surmounted by a dark object such as a fuel drum. Cairns are subject to

deflation by the wind and to burial by falling and drifting snow, but they generally survive for several months. The working life of fuel-drum trail markers can be extended by setting them on top of cairns.

Jettisoned containers and waste items: Up to now vehicles have frequently carried their spare fuel in 55-gal drums, and the empty barrels discarded along the trail provide effective markers. When sufficient unwanted drums (or other containers) are available they may be deliberately placed at fixed intervals along a trail. The drums are stood on end in shallow holes (to prevent blowing over) at perhaps ½-mile intervals and painted with a number and the distance along the trail. At key points, such as turns or entrances to crevassed sections, warnings are prominently displayed. In daylight with clear conditions (no fog or drifting snow), drums are good markers and trails marked with them can be picked up easily by aircraft and helicopters, even if other surface features are obliterated by whiteout. A drum standing only 3 ft or so above the surface will be buried by new snow sooner than a flag will, and its useful life as a marker would not be more than 3 years. In some areas single drums would be completely buried in 1 year. In Greenland, three or more drums have been welded end-to-end to form tall columns. These tall markers need additional support, e.g., steel angles driven into the snow alongside the drums.

There is no reason why trail markers need be neat uniform items; almost any large pieces of camp rubbish can be used, at least for filling gaps between markers which carry information. Old packing case timber, scrapped hardware, fire-damaged materials, etc., can all be taken out on sleds and dumped along a trail. While this is not elegant, it is effective and economical.

Visual markers are excellent in clear weather, but if a trail is to be followed in heavy drift or at night, markers must be closely spaced — not more than about 100 yards apart. This is not impossible to provide — indeed, a continuous line in the nature of a wire fence could be set up — but it would be expensive to place and maintain.

When trails are opened to traffic, rigid trail discipline is maintained so that vehicles always run along the same lane; this allows drivers to follow vehicle tracks at night or in poor visibility. If vehicles are allowed to wander off the trail, drivers who try to follow their tracks in poor visibility may be diverted away from the markers and forced to halt. There should also be a strict rule stipulating that wastes and sewage are to be dumped on one side of the trail (downwind, if possible), and snow for water supply is to be collected from the opposite side. Once a month somebody traveling over the trail should be made responsible for maintenance — replacing flags which have blown away or frayed badly, digging out badly drifted drums, or re-setting fallen stakes.

Electronic devices. Various novel trail marking concepts have been studied since 1954. They include radioactive pellet trails, magnetic particle trails, excited one- and two-wire transmission lines, radar targets and radio beacons. After initial study, only excited transmission lines and radar methods have been developed in the United States. Russian tractor trains in Antarctica are reported as using radio beacons and aircraft radio compasses but no details are available. The transmission line and radar methods are described briefly below.

Excited transmission lines:[10, 11, 21] The general idea of this system is that wires are laid in the snow along a trail and vehicles are equipped with detection apparatus which enables them to follow the buried wires. Early experiments were made with lines excited by direct current from power pulse transmitters placed at intervals along the line. It was later found that sine wave excitation was preferable and that detection of electromagnetic field was more suitable than electrostatic field detection because of the attenuation of electrostatic field with increasing snow depth over the wire and "peaking" of the signal.

An early single line system used one wire which was fed with power at audio frequency near the center point to energize it. The vehicle was fitted with loop antennas to pick up the magnetic field and a receiver which had a light panel giving indication of cross-trail position and a meter for indicating vehicle heading.

Although single and double wire systems could both be used over considerable distances, the double wire system was thought to be preferable and development was

concentrated on the two-wire line. The T-4 trail-following system employed two wires 75 ft apart and connected at the trail ends to form a single current path. Wires of #4 aluminum give optimum operating economy. Terminal equipment excites 60 miles of 2-wire line with 60-cycle single phase a-c power. Vehicles are equipped with a 3-loop antenna and a receiver for detecting and amplifying trailmarking signals induced in the antenna. The receiver control panel, shows vehicle heading and position in relation to the trail wires. Power is supplied from a dynamotor operating off vehicle batteries of 12 or 24 volts.

A method for detecting line breaks has been developed as part of the system; the break position is roughly located (within 5%) by measuring trail capacitance from the terminal end, and then accurately pin-pointed by measuring the electrostatic field along the wire in the break area, using a probe and vacuum tube voltmeter.

Radar trail following:[28] Early tests were made with a Raytheon Model 1500 Pathfinder radar set fitted to vehicles. It was found that ruts in snow could be detected at distances up to three-quarters of a mile and steel fuel drums were "visible" for three miles or more on straight sections of the trail. Falling snow gave no return and on a wavelength of 3.2 cm weather effects and the snow surface gave little or no return.

Tractor swings traveling the trail between Camp Tuto, Camp Century and Site 2 in Greenland were equipped with Raytheon radar sets. This set, mounted in the command wannigan, was capable of picking up metal poles, bamboo stakes, reflectors, fuel drums, and other objects along the trail. With the newly imposed demand for year-round travel on this north Greenland trail, it is expected that improved equipment will be provided for routine radar trail following.

Operation "Lead Dog" swings have been equipped with various sets for testing and evaluation. The following comments were made:[27,28]

(a) AN/SPN-11 ship radar — mounted in a command wannigan. It proved troublesome, particularly when the train was in motion.

(b) Bendix Marine MR-3B small vessel radar — installed in Weasel and Polecat. Gave good results. Refinement of equipment and mounting system would improve performance. Auxiliary generator is needed to provide 115 volt supply.

(c) SPS-35 ship radar — installed in the control cab of the Overland Train. Worked satisfactorily.

(d) Sperry Marine Radar System No. 5 — mounted in a Weasel. It was too fragile and unstable for regular trail use.

Crevasse detection

Crevasses constitute one of the greatest hazards met by vehicles traveling on a polar snowfield and a number of lives have been lost when vehicles plunged into them. Once located, a crevasse can be avoided, bridged, or filled with snow, but most crevasses above the firn line are concealed by snow bridges which often are not strong enough to carry the weight of a tractor. Light tractors, such as Weasels or Sno-Cats, often cross snow bridges over narrow crevasses, the vehicle being driven across at right angles to the line of the crevasse, but the procedure cannot be recommended since apparently narrow crevasses usually widen a few feet beneath the surface. For practical purposes all crevasses should be treated as dangerous, and vehicles should be driven across them only where they have been proved to be very narrow. The calculated risks taken by exploratory parties do not justify similar procedures in routine transport operations. Various crevasse detection methods are discussed below.

Visual detection. There are few crevassed areas which cannot be recognized as potential danger zones by experienced observers when lighting conditions are good, but newcomers to the polar regions may easily miss the indications. Crevasses are the natural result of tensile or shear strains on the surface of an ice sheet, and it is possible to recognize situations which favor development of these crevasse-forming strains. Appreciable convex curvature of the surface, flow disturbances caused by projecting or

submerged rock masses, flow accelerations where the ice channels into valleys, ice shelf boundaries — any indications of tension or shear in the ice surface give warning of potential danger. Unfortunately vehicles must often travel through areas which exhibit the general signs of potential crevassing (almost all of the marginal areas of Greenland and Antarctica come into this category) and so a close watch has to be kept on the surface so that the crevasses themselves are detected. Crevasses can often be spotted by the slight sagging of the snow bridge; low-angle sunlight is particularly favorable for showing them up. When a crevasse is widening the snow bridge will sometimes crack open slightly, or even collapse in places, giving an obvious indication. In regions subject to frequent drifting snow, however, these cracks and holes are soon re-bridged. Alongside big crevasses, particularly in Antarctica, heaps of snow, referred to as "haycocks" sometimes build up to form a row of snow mounds on each side of the crevasses. Their formation is associated with turbulent wind eddies above cracks and holes which appear along the abutments of the snow bridge. When a crevasse field has been located, concealed crevasses or sections of crevasse can often be anticipated from the general spacing and orientation. Crevasses do not terminate abruptly but taper off, getting narrower and narrower towards their ends. If, therefore, a visible crevasse disappears into featureless snow while it is still wide, it is almost a certainty that it continues for some distance under the snow.

Preliminary crevasse reconnaissance is best made from helicopters or slow-flying fixed-wing aeroplanes, such as the L-19 or L-20. The approximate locations of crevassed areas can be fixed by simple mapping or navigation techniques, and vertical photographs permit detailed mapping of detectable crevasses. Ground markers, such as weighted and flagged stakes, may be dropped from the air.

Some crevasses are just not visible to the eye; soft new snow is especially effective in disguising them. In this case other detection methods have to be adopted.

Probing. Hand probing is the traditional method of detecting concealed crevasses, and of testing the strength of snow bridges for crossings on foot or by light sled. The early Alpinists developed a safe procedure for probing, the leading man being roped to two or more companions who followed at intervals of 30 ft or more. In this kind of operation, skis or snowshoes decreased the likelihood of a man breaking through a snow bridge. This basic idea is still followed today for guiding vehicles through badly crevassed areas, although longer probing rods than the mountaineers' ice axe are used. The probe, a 15 ft rod about $\frac{1}{2}$ in. in diameter, is jabbed vigorously into the snow every 3 feet or so; when the snow is solid (or the snow bridge very thick) the probe "drives to refusal," but when over a crevasse it punches through the snow bridge. Once a crevasse is indicated, the area is probed so that the width and direction is defined. A simple crevasse pattern, such as a series of straight parallel cracks, can be adequately mapped in this way, but in the case of a group of sigmoidal shear crevasses it is much more difficult to define the general pattern.

This method is simple, and is probably the most reliable one available at present. A hand probe may fail to penetrate a very thick snow bridge, but this objection may be less serious in practice than in theory. A very thick snow bridge would generally be associated with a very wide crevasse (if on a narrow crevasse it might be safe anyway) and an isolated wide crevasse, not surrounded by lesser neighbors, could only occur in exceptional circumstances. The main objection to the method is its slowness.

Crevasse detecting instruments. A number of different principles for crevasse detection have been investigated, and some of the more promising ones have been followed up. A list of general methods which have been conceived is given below.

a. A system of surface electrodes, low frequency current source, and field sensing device which responds to anomalies of apparent dielectric constant.

b. A system of surface electrodes, balanced RF arrays, VHF beams and radio field strength detectors.

c. Reflection of directed beams of meter and centimeter radio waves.

d. Radio field profiling.

e. Measurements of RF antenna impedance at various antenna positions.

f. Seismic pulse velocity measurements.

g. Continuous wave seismic intensity measurements.

h. Seismic pulse reflections with discrimination against vertically moving energy by geophone arrays.

i. A low frequency airborne device measuring displacement eddy currents induced in the ice by a large primary coil, secondary search coils being suspended or arranged so as to prevent direct magnetic coupling to the primary coil.

j. Monitoring of gamma radiation and neutron reflection effects.

k. Microwave transmission and FM detection.

l. Thermal radiation sensing (infrared detection).

Some of these ideas are thought to be unpromising, others are believed to have merit but have not been adequately tested, and a few have been developed to something approaching the operational stage. The following developments have been carried out.

The "Dishpan" electrical crevasse detector[5]. This is the only detector in operational use at the present time, and is the outcome of principle a. above. The system is described diagrammatically in Figures 38-40. Low frequency (60-400 cps) alternating current is applied to the current electrodes and a "displacement current" is established in the ice (snow). A device for measuring potential difference, such as an a-c voltmeter, is connected between the detection, or signal, electrodes so that current density in the surrounding ice is measured. Crevasses distort the current pattern and cause voltage changes between the signal electrodes.

This type of detector was developed for the U. S. Army between 1954 and 1956 and improved versions were built for I. G. Y. operations in Antarctica. It was designed for continuous operation from a weasel, and two systems were installed on each vehicle, a "wide" system and a "long" system. The "wide" system consists of four electrodes arranged in an arc ahead of the weasel, while the "long" system comprises a leading electrode and the weasel as signal electrodes, and two current electrodes trailed behind the vehicle. Figure 39 shows a block diagram of the electrical system. The driver's twin indicators consist of milliammeters, alarm lights, and alarm buzzers. The unrectified a-c signal can also be heard through headphones if desired. Continuous traces of the signals are made in the twin recorder cabinet.

The detectors used in Antarctica in 1957-58 were considered successful. The wide system consistently recorded crevasses when the snow bridges were less than 10 ft thick, although signals over bridges 10 ft to 16 ft thick were confusing. Bridges more than 16 ft thick generally went undetected. The long system failed to produce consistent warning and extensive testing and overhaul did not improve the performance. General reactions of men involved with the early models range from enthusiasm to disparagement, photographs of detector weasels wedged in broken snow bridges occasionally being offered as cynical comment. Nevertheless, it seems that these detectors are useful aids for trail proving.

Thermal sensing. The circulation of air inside crevasses, and the movement of air through snow bridges with atmospheric pressure changes, can produce anomalous surface temperatures in the snow above crevasses, i. e., a snow bridge may be warmer or cooler than the surrounding unbroken snow masses. Thus the radiation from snow above a crevasse may differ from the general surface radiation, and infrared sensing devices can be used to detect these changes in long-wave radiation.

To test the principle of infrared crevasse detection, SIPRE* field tests were made with a thermal bolometer detector mounted on a 100 ft high test tower and also on a weasel. The device had a scanning head which focussed the radiation from the snow onto the sensing element, a thermistor flake connected in a bridge circuit with an identical

*Now USA CRREL

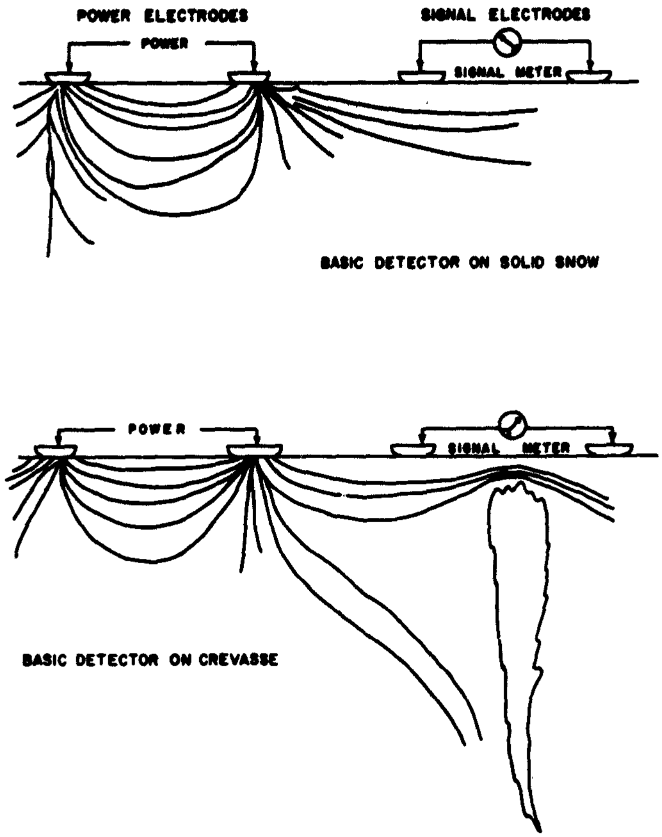

Figure 38. Schematic illustration of the way a "dishpan" electrical crevasse detector works. (After Cook, ref. 5; and U. S. Army TRAG, ref. 28)

compensating element. The signal produced by radiation heating of the sensing element was passed through an amplifier and made to modulate the light of a glow tube, the image of which was recorded on photographic film. The detector scanned an area by sweeping along parallel lines, the radiation being recorded along corresponding lines on the film.

This apparatus proved that the method is feasible for detecting crevasses in dry snow if the surface wind is not so strong that it obscures radiation differences. Thermal sensing cannot locate crevasses under wet snow, since the surface temperature of a snow and water mixture remains constant at 32F.

The final objective of the project was to produce an airborne system. Tests with existing systems showed that they are not satisfactory, primarily because they are not sensitive to radiation in the region of 8 to 14μ wavelength, where the radiation energy of a snowfield is concentrated. Tests with an airborne system which responds to radiation in the 8 to 14μ region have recently been conducted, and have indicated a high degree of success.

Crevasse crossings

When a crevasse has been located it can be circumvented or crossed. Since crevasses, like other troubles, rarely come singly, it is often better to avoid a crevasse

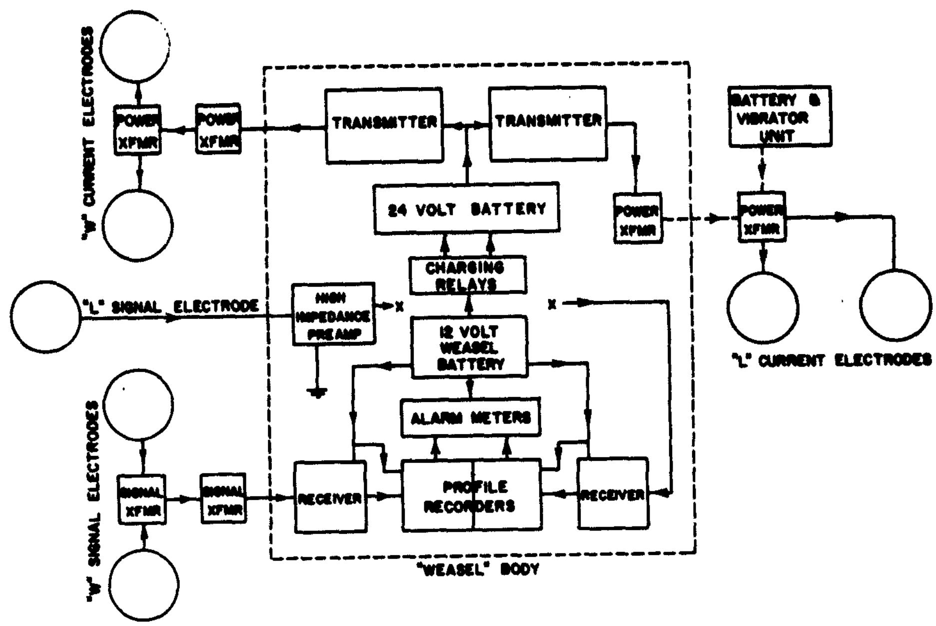

Figure 39. The components of a double crevasse detector. (After Cook, ref. 5)

field, even at the cost of many miles of extra travel. In some cases, however, it is impossible to go around, and wide crevasses have to be crossed. There are tow main techniques: bridging and filling.

Crevasse bridges. Light portable crevasse bridges made up from aluminum or steel slotted angle have occasionally been used by parties employing man-hauled or dog sledges, but the practice does not appear to have been usefully extended to vehicle movement.

In 1954 the U. S. Army prepared a light tactical bridge [15] with aluminum treadways for spanning crevasses up to 24 ft wide. The bridge was 40 ft long and supplementary material included two aluminum launching noses, a launching roller, and a sled with rocker. No information on the bridge's performance in the field is available.

Crevasse filling. Artificial bridging calls for expensive fabrication and transport, and after a bridge has been placed it must constantly be lifted and adjusted to combat snow accumulation and ice movement. A more satisfactory solution to the crossing problem is to fill a section of crevasse with snow so that vehicles can cross on a solid plug.

The filling operation can be divided into two parts: blowing and blading. After a crevasse has been detected it is carefully probed by roped men secured to tow hitches or belays so that its limits are defined. A hole, about 3 in. diameter, is augered on one lip of the crevasse, charged with explosive, and fired to blast open the snow bridge. The crevasse is then re-examined, and further shot holes are drilled to complete the snow bridge demolition. The thick cornice, or snow bridge abutment, at the lip of a crevasse can be knocked down by placing charges along it at 5-7 ft centers.

Two main types of explosives are used: composition C-3 and C-4, and 30-40 percent dynamite. The composition is very stable at all temperatures, the dynamite is

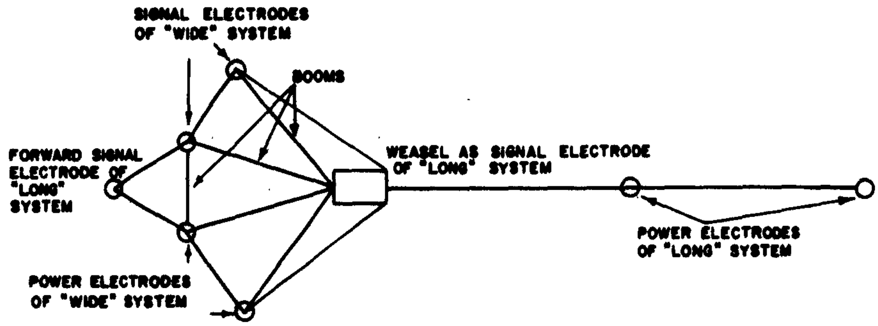

Figure 40. Arrangement of a double crevasse detector on a Weasel.

somewhat less stable. The composition can be moulded into shaped charges or mixed with engine oil in ratios up to one part oil to two parts explosive (by weight). The dynamite is commonly used in groups of seven sticks. The amount of explosive in each shot hole is chosen to suit the job, 2-6 lb per hole usually being ample for medium to thick bridges.

Charges are detonated with an electric blasting cap, which can be fired by touching the ends of the firing line to the terminals of a vehicle battery. The firing vehicle should be 40 yards away from the blast; unsheltered personnel should be no closer than 75 yards, and on the windward side.

Narrow crevasses, those proved by deep probing to be less than 3 ft wide, can be opened by blading. The tractor is run almost parallel to the crevasse, approaching it at a shallow angle until the corner of the blade projects into the crevasse. This breaks the bridge, and successive passes are made to push fill into the crevasse. Shallow cuts are made from both sides of the trail (which is aligned to cross at right angles to the crevasse) until the fill reaches surface level, and one track is gradually moved out onto the fill to compact it. Final compactive passes are made along the line of the trail. In filling a wide crevasse, initial cuts are made at right angles to the crevasse to clear loose snow and enlarge the opening. Later cuts are angled in from both sides of the trail until fill reaches surface level. With passes almost parallel to the crevasse, the tracks are eased out onto the fill to compact it, and the final passes are made along the line of the trail (at right angles to the crevasse).

Once a trafficable plug has been placed and compacted it is clearly flagged and subsequently kept under observation so that any further opening can be compensated by extra filling and compacting.

On military swings one tractor, usually the one hauling the command train, is fitted with a blade so no special equipment has to be brought in to fill crevasses.

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APPENDIX A.

OVERSNOW VEHICLES — DATA SHEETS

Note: Some of the figures listed in this section should be regarded with caution; e.g., the maximum speeds given may refer to maximum speed attainable on a snow-free highway or on smooth hard-packed snow. Some of the vehicles listed are no longer manufactured.

U. S. Vehicles.

- M29C Weasel
- M76 Otter
- M-7 half-track
- M-4 high-speed tractor
- M5A4 high-speed tractor
- M8E2 cargo tractor
- M59 personnel carrier
- T-116 amphibious cargo carrier
- M55 LGP D-8 tractor
- Caterpillar D-4
- Caterpillar D-6
- John Deere 420
- Pack-Rat
- Sno-Cat 443
- Sno-Cat 743
- Sno-Cat 423
- Sno-Kitten 222
- Sno-Cat 843
- Polecat
- Sno T'rrain
- Wagner Transporter
- Musk-Ox
- Trackmaster 4-T.10-N
- Kristi KT-2A
- Kristi KT-3
- Kristi KT-4
- WNRE Dinah
- Sno-Traveler motor toboggans
- Gulf Marsh Buggy
- Le Tourneau Sno Buggy
- Overland Train
- Jeep with flotation tire conversion
- Polecat Mk. II

Canadian Vehicles.

- Canadair Rat
- Bombardier Muskeg Carrier, Model S
- Bombardier Muskeg Carrier, Model HDW
- Bombardier Muskeg Tractor, Model M-8
- Bombardier Muskeg Tractor, Model J-5
- Bombardier 4-track drive freighter, Model MM
- Bombardier Snowmobile
- Bombardier Carrier, Model BB-60
- Bombardier Ski-Doo
- Eliason motor toboggan
- Nodwell 3-axle carrier, Model RN 21
- Nodwell 3-axle carrier, Model RN 50
- Nodwell 3-axle carrier, Model RN 75
- Nodwell 4-axle carrier, Model RN 110
- Nodwell 4-axle carrier, Model RN 140
- Nodwell 8-axle 4-track Transporter, Model RN 200

Russian Vehicles.

- Kharkovchanka (Bogatyr)
- Pingvin
- GAZ-47
- S-80
- S-100A
- S-100AB
- "Heavy duty tractor"
- "Modernized heavy-duty tractor"

Swedish Vehicles.*

- Snow-Trac SR2

British Vehicles.

- Ferguson farm tractor, Model TE 20

*Sweden has an articulated 2-unit military vehicle similar to the Polecat, but no details are available.

Weasel amphibious cargo carrier — Ordnance number M29C

Manufacturer: Ordnance — Studebaker

Description: General purpose amphibious tractor — used for personnel and light freight carrying and for light sled haulage. (There is a non-amphibious version designated M29.) An outstanding vehicle which has long been the mainstay of oversnow transportation for many Western countries (Fig. 11).

Engine: Studebaker Champion 6-cylinder, 65 hp

Transmission: 3 &1 gearbox and 2 axle ratios

Fuel capacity: 35 gal

Fuel consumption: 5 mpg

Payload: 1200 lb in standard ordnance condition

Overall length: 192 in.

Overall width: 67 in.

Overall height: 71 in. with ordnance canopy

Vehicle weight: 4800 lb (heavier with built-on cabin)

Freeboard at gross weight: 10½ in. bow, 8 in. stern

Track: steel track plates with flexible connectors and endless rubber bands. Vehicle weight carried on 32 bogey wheels.

Track width: 15 in. (M29), 20 in. (M29C)

Nominal ground pressure: 1.9 psi (light)

Ground clearance: 11 in.

Turning radius: 12 ft

Maximum allowable speed: 36 mph

Otter amphibious cargo carrier — Ordnance number M76

Manufacturer: Ordnance — General Motors

Description: Amphibious carrier for cargo and personnel. Tracks consist of rubber bands with steel cross links running around pneumatic tires. Only limited success in snow (Fig. 23).

Engine: 4-cylinder opposed air-cooled Continental, 127 hp

Transmission: automatic; 2 forward ranges and 1 reverse

Final drive: through rubber front sprockets

Fuel capacity: 60 gal

Fuel consumption: 2.3 mpg

Overall length (propeller in land traveling position): 193 in.

Overall width: 98 in.

Overall height: 108 in.

Vehicle weight (fighting): 12,200 lb

Track: rubber bands with steel cross links, 30 in. wide

Wheels: 16

Nominal ground pressure: 2.1 psi

Ground clearance: 16¾ in.

Turning radius: pivots in own length

Governed speed: 28 mph

M-7 half-track

Manufacturer: Ordnance — Allis Chalmers

Description: A light 2-seat half-track with front end skis. Used extensively by CRREL as a test vehicle.

Engine: Willys Jeep 63 hp

Transmission: 6 and 2

Fuel capacity: 10 gal

Payload: 2 passengers or 500 lb

Overall length: 14 ft 4 in.

Overall width: 5 ft 3 in.

Overall height: 5 ft 4 in.

Vehicle weight: 2, 600 lb

Track area: 2, 540 in.^{2}

Ski area: 700 in.^{2}

Nominal ground pressure: 0.9 psi (light); 1.0 psi (loaded)

Ground clearance: 14 in.

Steering: steerable skis

Maximum speed: 20 mph

Cruising speed: 12 mph

M-4 high-speed tractor

Manufacturer: Ordnance

Description: Soft terrain vehicle for carrying personnel and light cargo and for hauling artillery. Only suitable on firm icecap snow and seasonal snow up to 30 in. deep.

Engine: Waukesha 6-cylinder, 190 bhp at 2100 rpm

Overall length: 210 in.

Overall width: 97 in.

Overall height: 108 in.

Vehicle weight (fighting): 31, 400 lb

Nominal ground pressure: 7.6 psi

Ground clearance: 20 in.

Turning radius: 18½ ft

Maximum allowable speed: 35 mph

M5A4 high-speed tractor

Manufacturer: Ordnance

Description: For transporting personnel and light cargo over soft terrain, and for hauling artillery. Ground pressure too high for deep (> 30 in.) soft snow.

Engine: Gasoline, 235 hp at 2900 rpm

Weight (for oversnow evaluation): 24,000 lb

Track: Contact length 118 in., width 12 in.

Nominal ground pressure: 8.4 psi

Ground clearance: 17 in.

M8E2 cargo tractor

Manufacturer: Ordnance

Description: Military vehicle for transporting personnel and cargo, and for hauling artillery. Unsuitable for deep soft snow.

Engine: Continental 6-cylinder air-cooled, 363 bhp at 2800 rpm

Payload: 17,500 lb

Loading height: 58 in.

Cargo space: 650 ft^3

Overall length: 265 in.

Overall width: 130 in.

Overall height: 120 in.

Vehicle weight (empty): 37,500 lb

Nominal ground pressure: 8.3 psi

Ground clearance: 19 in.

Turning radius: pivots

Maximum speed: 40 mph

M59 personnel carrier

Manufacturer: Ordnance

Description: Heavy personnel carrier for soft terrains. Unsuitable for deep soft snow.

Engine: 2 gasoline engines, each developing 127 hp at 3350 rpm

Weight (for oversnow evaluation): 38,700 lb

Track: Contact length 132 in., width 21 in.

Nominal ground pressure: 7.0 psi

Amphibious cargo carrier T-116

Manufacturer: Ordnance

Description: Full-tracked amphibious carrier for personnel and light cargo.

Engine: Continental, 100 hp at 4,600 rpm

Fuel capacity: 75 gal

Rated payload: 3,000 lb

Overall length: 182 in.

Overall width: 80½ in.

Overall height: 79½ in.

Curb weight: 5,350 lb

Ground contact length: 98 in.

Ground contact width: 20 in.

Nominal contact area: 3,920 in.^{2}

Nominal ground pressure: 2.2 psi (loaded)

Ground clearance: 15½ in.

Turning radius: pivots

Maximum speed: 40 mph

LGP D-8 tractor (M55)*

Manufacturer: Modification of Caterpillar D-8 construction tractor (Caterpillar Co., Peoria, Illinois)

Description: Prime mover for hauling heavy sled trains. Usual version has bow fuel tank, no blade, and rear winch. Standard U. S. prime mover for operations in Greenland and Antarctica. Very sturdy and reliable (Fig. 13).

Engine: Caterpillar D342 diesel, 205 hp

Fuel capacity: 768 gal

Overall length: 288 in.

Overall width: 160 in.

Overall height: 126 in.

Curb weight: 72,000 lb

Ground contact length: 170 in.

Ground contact width: 52 in. (one track)

Nominal contact area: 17,680 in.^{2}

Nominal ground pressure: 4.1 psi

Ground clearance: 13 in.

Turning radius: 24 ft

Maximum speed: 5.2 mph

*Minor model changes have been made from time to time, varying the specifications slightly.

Caterpillar D-4

Manufacturer: Caterpillar Tractor Co., Peoria, Illinois

Description: Engineer tractor which has been used in Antarctica for sled-hauling with payloads of 10 - 15 tons. Widest and longest available track used for oversnow operation. Can be fitted with blade and/or winch.

Engine: 4-cylinder CAT diesel, 63 hp

Fuel capacity: 30 gal

Length: 10 ft (without blade)

Width: 6 ft 6 in.

Weight: 11,500 lb (without blade, winch or cab)

Track contact length: 6 ft (5-roller track frame)

Track width: 24 in. (widest available)

Nominal ground pressure: 3.5 psi (without blade or winch)

Ground clearance: $11\frac{1}{2}$ in.

Maximum speed: 6 mph

Caterpillar D-6

Manufacturer: Caterpillar Tractor Co., Peoria, Illinois

Description: Engineer tractor which can be used for sled-hauling on firm snow.

Engine: 6-cylinder CAT diesel, 93 hp

Fuel capacity: 48 gal

Length: 12 ft 3 in.

Width: 7 ft $9\frac{1}{2}$ in.

Weight: 18,200 lb (without blade, winch or cab)

Track contact length: 86 in.

Track width: 24 in. (widest available)

Nominal ground pressure: 4.5 psi (without blade or winch)

Ground clearance: $12\frac{1}{2}$ in.

Maximum speed: 6.6 mph

John Deere 420 crawler

Manufacturer: John Deere Tractor Co., Moline, Illinois

Description: Small engineer tractor suitable for sled-hauling.

Engine: 2-cylinder gasoline, 30 hp

Fuel capacity: $10\frac{1}{2}$ gal

Length: 102 in. (no blade)

Width: 60 in.

Weight: 4,700 lb

Track contact length: $66\frac{1}{2}$ in. (5-roller track frame)

Track width: 14 in. (widest snow track)

Nominal ground pressure: 2.5 psi

Ground clearance: 12 in.

Maximum speed: 7.3 mph

Pack-Rat

Manufacturer: Twin Coach Co., Buffalo, New York

Description: Amphibious light cargo carrier.

Engine: American Motors 4-cylinder, 55 hp at 3600 rpm

Fuel capacity: 16 gal

Payload: 2,000 lb on land, 1,000 lb on water

Length: 117½ in.

Width: 68 in.

Height: 37 in.

Curb weight: 2,800 lb

Turning radius: 6 ft

Maximum speed: 35 mph on land, 4 mph on water

Sno-Cat Model 443

Manufacturer: Tucker Corporation, Medford, Oregon

Description: 6- to 8-passenger vehicle running on 4 ladder-tracked pontoons. Excellent in deep soft snow. Climbs and sidehills well.

Engine: 95 hp Chrysler

Transmission: 3 & 1

Fuel capacity: 35 gal

Fuel consumption: 5 - 6 mpg

Load capacity: 1350 lb

Trailer capacity: 2500 lb

Overall width: 6 ft 3 in.

Overall length: 15 ft 10 in.

Overall height: 7 ft 5 in.

Weight: 3990 lb

Pontoon and track : 18 x 84 in.

Nominal ground pressure: 0.91 psi (fully loaded)

A heavy duty model, 443-A, is made, a 115-hp Chrysler engine being used with a 4 & 1 transmission. The load capacity of the heavy duty model is 1650 lb and the vehicle weight is increased to 4200 lb.

Flat-deck cargo versions of the above vehicles are made, the standard model being designated 442 and the heavy duty model 442-A. Two passengers can be carried in the driver's cab and the load capacities are identical to those of the enclosed 443 series, i.e., 1350 and 1650 lb.

Sno-Cat Model 743

Manufacturer: Tucker Corporation, Medford, Oregon

Description: Enclosed 15-passenger carrier running on 4 ladder-tracked pontoons. Outstanding in soft snow. Climbs extremely well and conforms to terrain irregularities easily (Fig. 16).

Engine: 180 - 235 hp Chrysler V8

Transmission: 3 & 1

Fuel capacity: 50 gal

Fuel consumption: 3 - 5 mpg

Load capacity: 2300 lb

Trailer capacity: 6000 lb

Overall width: 7 ft 5 in.

Overall length: 20 ft

Overall height: 7 ft 9 in.

Weight: 7200 lb

Pontoon and track: 24 x 103 in.

Turning radius: 28 ft

The heavy duty model, 743-A, has a 5 & 1 transmission and weighs 7400 lb. The load capacity is 2750 lb, the trailer capacity 7500 lb, and the fuel consumption is reduced to 2 - 4 mpg.

Flat-deck freighters are available, the 742 standard model and the 742-A heavy duty model. These have 3-passenger driving cabs, the load capacities are the same as the 743 series, and the trailer capacities are 7500 for both models. Both have 5 & 1 transmissions and the vehicle weights are 7100 and 7300 lb respectively.

Sno-Cat Model 423

Manufacturer: Tucker Corporation, Medford, Oregon

Description: 2 - 4 seat enclosed passenger carrier running on 2 ladder-tracked pontoons and 2 front-end skis (with retractable wheels).

Engine: 95 hp Chrysler

Transmission: 3 & 1

Fuel capacity: 18 gal

Fuel consumption: 6 - 8 mpg

Load capacity: 800 lb

Trailer capacity: 1000 lb

Overall width: 6 ft 3 in.

Overall length: 17 ft 4 in.

Overall height: 6 ft 5 in.

Weight: 2500 lb

Pontoon and track: 18 x 84 in.

Ski size: $\frac{7}{8}$ x 9 x 90 in. (hickory)

Turning radius: 25 - 30 ft

All Sno-Cats have Dodge truck differentials and transmissions. Their cruising speeds are in the range, 10 - 15 mph.

Sno-Kitten Model 222

Manufacturer: Tucker Corporation, Medford, Oregon

Description: 2-passenger sedan running on 2 ladder-tracked pontoons.

Engine: Ford Anglia, 35 hp

Transmission: 3 & 1

Fuel capacity: 15 gal

Fuel consumption: 10 - 12 mpg

Load capacity: 650 lb

Trailer capacity: 1000 lb

Overall width: 56 in.

Overall length: 92 in.

Overall height: 70 in.

Weight: 1600 lb

Pontoon and track: 18 x 85 in.

Turning radius: Own length

Sno-Cat Model 843-Antarctic

Manufacturer: Tucker Corporation, Medford, Oregon

Description: Special vehicle for long-distance scientific traverses in Antarctica. Large box body mounted on Sno-Cat pontoons, and fitted out for sleeping and for scientific work. Considerable towing capacity (up to 15,000 lb drawbar pull) permits fuel and supplies to be hauled in sleds, trailers, and rolling liquid transporters.

Engine: Cummins 6-cylinder diesel, 175 hp at 2,500 rpm (turbocharged)

Transmission: 5 & 1

Fuel capacity: 80 gal

Load capacity: 6,000 lb

Length: 25 ft

Width: 9 ft 5 in.

Height: 10 ft 10 in.

Weight (empty): 21,000 lb

Pontoons and tracks: 4 pontoons, each 32 in. x 125 in. overall

Nominal ground pressure: 1.4 psi (light), 2.1 psi (fully laden)

Turning radius: 44 ft

Speed: 10 mph cruise, 17 mph maximum

Polecat*

Manufacturer: Wilson, Nuttall and Raimond, Inc., Chestertown, Maryland

Description: Articulated 2-unit carrier for personnel and light cargo. Drive on all tracks, which are Weasel-type. Articulation minimizes pitching and permits continuous-traction steering (Fig. 12).

Engine: International BD-264, 120 hp at 3,000 rpm

Fuel capacity: 70 gal

Rated payload: 2000 to 3000 lb

Overall length: 292 in.

Overall width: 72 in.

Overall height: 80 in.

Curb weight: 10,000 lb

Ground contact length: 156 in.

Ground contact width: 20 in.

Nominal contact area: 6,240 $in.^2$

Nominal ground pressure: 2.1 psi (loaded)

Ground clearance: 10 in.

Steering: Angular displacement between units

Turning radius: 24 ft

Maximum speed: 17 mph

*Specifications change slightly with development of new models

Sno T'rrain

Manufacturer: Consolidated Industries, Dover, Delaware

Description: Light articulated 2-unit personnel carrier with 4-track drive. Employs Weasel tracks and is generally similar to the Polecat.

Engine: 264 $in.^3$ 6-cylinder International Harvester

Fuel capacity: 70 gal

Weight: 9900 lb

Nominal ground pressure: less than 1.5 psi

Ground clearance: 14 in.

Turning radius: 19 ft

Maximum speed: 36 mph

Operating speed: 26 mph

<u>**Wagner 7½-ton Transporter**</u>

Manufacturer: Wagner Mining Scoop Co., Portland, Oregon

Description: 2-unit articulated freight carrier with 4-track drive. 2-axle front unit carries engine and cab, while 3-axle rear unit mounts the cargo tray.

Engine: 320 hp diesel

Payload: 15,000 lb

Vehicle weight: 25,500 lb

Steering: Horizontal angular displacement at the articulation pivot

Suspension: Rigid

Tracks: Flexible belts with steel grousers and inside guides running around pneumatic tires

<u>Musk-Ox articulated cargo carrier</u>

Manufacturer: Wilson, Nuttall and Raimond, Inc., Chestertown, Maryland

Description: Heavy articulated cargo carrier with drive on 4 flexible tracks. Designed initially for work over the snow and muskeg of northern Canada (Fig. 20).

Engine: Cummins V-8, 450 hp at 2,500 rpm

Fuel capacity: 400 gal

Rated payload: 40,000 lb

Overall length: 583 in.

Overall width: 120 in.

Overall height: 122 in.

Curb weight: 50,000 lb

Ground contact length: 119 in. front, 173 in. rear

Track width: 52 in.

Nominal contact area: 30,400 $in.^2$

Nominal ground pressure: 3.0 psi (loaded)

Steering: Angular displacement between front and rear units

Turning radius: 42 ft

Maximum speed: 17 mph

Trackmaster

Manufacturer: Thiokol Chemical Corp., Logan, Utah

Description: Light personnel carrier employing flexible tracks consisting of rubber belts and steel crosslinks running around single-row pneumatic tires (Fig. 17).

Engine: 130 hp Ford Industrial 6-cylinder Series 223

Transmission: 3 & 1 Ford heavy duty

Fuel capacity: 19 gal

Carrying capacity: 2000 lb or driver and 7 passengers

Length: 142 in.

Width: 94 in.

Height: 84 in.

Weight (empty): 4800 lb

Track width: 31.5 in. (widest track fitted)

Track area: 6460 in.^{2}

Nominal ground pressure: 0.8 psi empty, 1.1 psi fully loaded

Tires: 6.40 x 15 standard automotive

Drive sprockets: Steel rear sprockets with $\frac{1}{2}$ in. vulcanized rubber coating

Ground clearance: 15 in.

Steering: Separate track speed controls through twin gear boxes and differentials

Turning radius: 15 ft

Maximum speed: 35 mph

Kristi Model KT-2A

Manufacturer: Kristi Co., Denver, Colorado

Description: Light tracked carrier for personnel or cargo. Has accessories for plowing or packing snow. Uses lightweight fiberglass body.

Engine: 36 hp Volkswagen or Porsche industrial engine

Transmission: 8 & 4 (with high-low range)

Fuel capacity: 20 gal

Fuel consumption: up to $1\frac{1}{2}$ gal/hr

Seating capacity: 4

Length: 9 ft 8 in.

Width: 7 ft 4 in.

Height: 5 ft 6 in.

Vehicle weight: 1800 lb

Maximum gross weight: 2800 lb

Track: Nylon-cotton belts with cross-cleats running around eight 4-ply 6.00 x 6 balloon tires (4 tires each side). Track is 24 in. wide.

Nominal bearing pressure: 0.5 psi with standard track, 0.4 psi with track extension

Maximum speed: 20 mph

Kristi Model KT-3

Manufacturer: Kristi Co., Denver, Colorado

Description: Light tracked carrier for personnel or cargo. Has lightweight fiberglass body and can be fitted with accessories for plowing or packing snow.

Engine: 36 hp Volkswagen or Porsche industrial engine

Transmission: 8 & 4 (with high-low range)

Fuel capacity: 20 gal

Fuel consumption: up to $1\frac{1}{2}$ gal/hr

Seating capacity: 5 - 6 (will accommodate a stretcher)

Length: 11 ft

Width: 7 ft 4 in.

Height: 5 ft 9 in.

Vehicle weight: 2100 lb

Maximum gross weight: 3600 lb

Track: Nylon-cotton belts with cross-cleats running around eight 6-ply 6.90 x 9 tires (4 tires each side). Track width 24 in.

Nominal bearing pressure: 0.5 psi

Maximum speed: 20 mph

Kristi Model KT-4

Manufacturer: Kristi Co., Denver, Colorado

Description: Amphibious light cargo and personnel carrier. Fiberglass body on steel frame.

Engine: 80 hp air-cooled or 65 hp marine

Payload: Driver and 8 passengers or 2000 lb cargo

Length: 11 ft 6 in.

Width: 6 ft 6 in.

Vehicle weight: 2800 lb

Track: Nylon-cotton belt with hickory cross-cleats, 24 in. wide. Each track runs around 4 pneumatic tires and is driven by an aluminum and rubber sprocket.

Steering: Controlled differential

Maximum speed: 25 mph on snow, 5 mph in water

WNRE Dinah

Manufacturer: Wilson, Nuttall, Raimond Engineers Inc., Chestertown, Maryland

Description: Amphibious two-unit 4-track vehicle for passengers or light cargo. Front unit carries driver and engine, rear unit carries payload.

Engine: 42 hp gasoline

Payload: 1000 lb or 6 passengers

Length: 17 ft

Width: 5 ft

Vehicle weight: 3300 lb

Track: Rayon-nylon belt with steel shoes, 20 in. wide. Drive on all 4 tracks.

Nominal ground pressure: 1.5 psi

Steering: Angular displacement at the articulation pivot

Maximum speed: 12 mph on snow, 2 mph in water

Sno-Traveler motor toboggans

Manufacturer: Polaris Industries Inc., Roseau, Minnesota.

Description: Several models of the Sno-Traveler motor toboggans are available. All are light personnel vehicles capable of towing light sledges or skiers. They have steerable skis and a cleated track for propulsion.

	K70A, K70B Trailblazer	K95, K95E Ranger	O13, O13E Trailmaster
Engine	Kohler 7 hp single-cylinder air-cooled	Kohler 9.6 hp single-cylinder air-cooled	Onan 12.9 hp twin-cylinder air-cooled
Drive	V-belt	V-belt	V-belt
Length	8 ft 6 in.	10 ft	11 ft 2 in.
Width	30 in.	36 in.	36 in.
Height	30 in.	36 in.	36 in.
Weight	470 lb	550 lb (+50 lb for electrical equipment)	670 lb (+50 lb for electrical equipment)
Seating capacity	1 or 2	2	2
Max towing capacity	500 lb	1000 lb	1200 lb
Track	Nylon belt with heavy-duty roller chain and steel cross-cleats		
Track bearing area	15 x 60 in. (900 in.^{2})	16 x 70 in. (1120 in.^{2})	16 x 86 in. (1376 in.^{2})
Skis	Main skis of treated wood, steerable front-end skis of steel with spring shock-mounting		
Maximum speed	15 mph	20 mph	24 mph

Model TK70 — Twin-Trailblaser: This is a lengthened version of the K70 model. It has two seats and two engines (7-hp Kohlers) in tandem. Each engine powers a separate drive track. Mobility can be maintained on one engine in case of mechanical trouble in the other.

Sno-Traveler Sportsline: This is a very small motor toboggan produced at low cost. It does not have main skis like the other Sno-Traveler models and runs on only steerable front-end skis and a broad single drive track.

Gulf Marsh Buggy

Description: Large-wheel amphibious vehicle.

Engine: 100 hp gasoline

Payload: 2550 lb

Gross weight: 18,000 lb

Tires: 10 ft diameter, 1 - 5 psi inflation pressure

Maximum speed: 30 mph

LeTourneau Sno Buggy

Manufacturer: Le Tourneau Co.

Description: Experimental large-wheel vehicle from which the Overland Train was developed.

Engine: 300 hp gasoline (driving generator)

Drive: Individual electric motors on wheels

Payload: 4000 lb

Gross weight: 48,000 lb

Tires: 4 sets of dual wheels, each with 10 ft OD tire, 5 psi minimum inflation

Speed: 10 mph

Overland Train

Manufacturer: Le Tourneau Co.

Description: Multi-unit freight train consisting of a prime mover and freight cars. Running gear consists of large diameter wheels with low-pressure pneumatic tires.

	Prime mover	Cargo car
Engine:	Cummins diesel, 600 hp at 2100 rpm	
Fuel capacity:	500 gal	
Payload:		30,000 lb
Overall length:	486 in.	534 in. (incl. tongue)
Overall width:	168 in.	168 in.
Overall height:	176 in.	120 in.
Curb weight:	58,580 lb	30,380 lb
Wheel base:	25 ft	25 ft
Tire size:	120 in. diam 48X68, Nylon, tubeless shallow tread	
Normal inflation:		12 psi
Ground clearance:	36 in.	36 in.
Turning radius:	65 ft	65 ft
Maximum speed:	17 mph	17 mph

Jeep with flotation tire conversion

Manufacturer: Flotation-wheel kit for Jeep or similar vehicles made by Terra Engineering Co., Lexington, Mass.

Description: Low pressure balloon tire for use on light 4-wheel drive vehicles. Following data for maximum flotation condition (minimum inflation pressure).

Tire diameter: 37 in.

Inflation pressure: 6 psi

Load per wheel: 950 lb

Footprint area: 155 in.^{2}

Tire deflection: 31%

Nominal ground pressure: 6 psi at 950 lb/wheel

Recommended speed: 15 mph

Polecat Mk. II

Manufacturer: Wilson, Nuttall and Raimond Inc., Chestertown, Maryland.

Description: Articulated 2-unit carrier for personnel and light cargo. Much bigger than original Polecat, having seating for 30 passengers. Still under development.

Engine: V-8 Cummins diesel, 265 hp at 2,600 rpm

Transmission: 5 &1

Fuel capacity: 190 gallons

Rated payload: 1,800 lb front unit, 5,000 lb rear unit

Overall length: 16 ft 10 in. front unit, 23 ft 9 in. rear unit

Overall width: Front unit 10 ft 10 in. (reducible to 8 ft 11 in.), rear unit 8 ft 11 in.

Overall height: Front unit 12 ft 6 in. (reducible to 9 ft 6 in.), rear unit 9 ft 10 in. (reducible to 9 ft 6 in.).

Dry weight: 15,200 lb front unit, 9,000 lb rear unit, 24,200 lb total

Curb weight: 17,200 lb front unit, 9,750 lb rear unit, 27,000 lb total

Gross weight: 19,000 lb front unit, 15,000 lb rear unit, 34,000 lb total

Track: Rubber belts with aluminum grousers running around special treadless tires, 7.10 x 15, 8-ply, inflated to 50 psi. Track width 35 in.

Nominal ground pressure: 2.6 psi

Steering: Angular displacement between units. 3-cylinder hydraulic control.

Maximum speed: 25 mph on hard surface, 20 mph on firm snow

Seating capacity: 10 and driver in front unit, 20 reclining seats and couch in rear unit.

CANADIAN VEHICLES

Canadair Rat

Manufacturer: Canadair Ltd., Montreal, Canada

Description: Light articulated cargo carrier with drive on 4 tracks.

Engine: Volkswagen, 34 hp at 3400 rpm

Fuel capacity: 23 gal

Rated payload: 600 lb

Overall length: 157 in.

Overall width: 48 in.

Overall height: 61 in. (to top of screen)

Curb weight: 1300 lb

Ground contact length: 41 in. (each unit)

Ground contact width: 20.5 in.

Nominal contact area: 1680 $in.^2$

Nominal ground pressure: 1 psi (loaded)

Turning radius: 13 ft

Maximum speed: 10 mph

Bombardier Muskeg Carrier Model S

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Universal flat deck carrier running on flexible tracks around pneumatic tired wheels.

Engine: 115-hp Chrysler 6

Transmission: 3 & 1

Final drive: Through rubber sprockets

Payload capacity: 6000 lb

Overall length: 11 ft 8 in.

Overall width: 7 ft 3 in.

Overall height: 7 ft 4 in.

Deck length: 6 ft 10½ in.

Deck width: 7 ft 0 in.

Vehicle weight: 5400 lb

Track type: Rubber belts with steel cross links, 28 in. wide

Wheels: 16 wheels, each fitted with 4.50 x 16 6-ply nylon Bombardier-type tires

Nominal ground pressure: (unloaded): less than 1 psi

Turning radius: 15 ft

Maximum speed: 16 mph

Cruising speed: 8 mph

<u>Bombardier Muskeg Carrier</u> Model HDW

This is basically similar to the Model S carrier, but the cargo deck tilts and a hydraulic winch is carried. The vehicle weight is nearly 2000 lb more than the Model S.

<u>Bombardier Muskeg Tractor</u> Model M-8

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: General purpose light tractor for personnel and freight carrying and for mounting special equipment. Runs on flexible tracking around pneumatic-tired wheels (Fig. 15).

Engine: 115-hp Chrysler 6

Transmission: 4 & 1

Final drive: Through 4 rubber sprockets

Fuel capacity: 18 gal

Payload capacity: 2500 lb

Overall length: 11 ft 8 in.

Overall width: 7 ft 3 in.

Overall height (with cab): 5 ft 8 in.

Vehicle weight: 4700 lb

Track type: $5\frac{1}{2}$ in. wide reinforced rubber belts with steel crosslinks

Wheels: 16 wheels, each fitted with 4.50 x 16 6-ply nylon tires

Nominal ground pressure: less than 1 psi (unloaded)

Ground clearance: 14 in.

Turning radius: 15 ft

Maximum speed: 25 mph

<u>Bombardier Muskeg Tractor</u> Model J-5

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Small general-purpose tractor. Running gear of the Bombardier type but with single wheels substituted for dual wheels.

Final drive: Through 2 rubber sprockets

Track type: Rubber belts with steel crosslinks

Wheels: 6 wheels, each fitted with 4.50 x 16 6-ply nylon tires

Bombardier 4-track Drive Freighter Model MM

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Two-unit articulated freight carrier with 4-track drive. Running gear consists of flexible open tracking round pneumatic-tired wheels.

Engine: 180 hp Chrysler V8

Transmission: 4 & 1

Final drive: Through rubber sprockets on 4 tracks

Payload capacity: 10,000 lb

Overall length: 27 ft 3 in.

Overall width: 7 ft 3 in.

Overall height: 7 ft 5 in.

Platform length: 20 ft 3 in.

Platform width: 7 ft 0 in.

Vehicle weight: 11,400 lb

Track type: Rubber belts with steel crosslinks, 28 in. wide

Wheels: 32 wheels, each fitted with 4.50 x 16 6-ply nylon Bombardier type tires

Nominal ground pressure (unloaded): 1 psi

Turning radius: 28 ft

Maximum speed: 17 mph

Cruising speed: 8 mph

Bombardier Snowmobile

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Enclosed passenger-carrying vehicle. Running gear consists of 2 Bombardier tracks and 2 front-end skis. High speed potential.

Engine: 115 hp Chrysler 6 or 180 hp Chrysler V8

Transmission: 3-speed

Final drive: Through 2 rubber sprockets

Payload capacity: 12 to 15 passengers, or 3000 lb

Vehicle weight: 3600 lb

Track type: Rubber belts with steel cross links

Wheels: 8 wheels, each fitted with 4.50 x 16 6-ply nylon tires

Skis: 2 front-end steerable skis

Maximum speed: 45 mph

<u>Bombardier Carrier</u> Model BB-60

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Lightweight amphibious tractor for personnel and light freight carrying. Has no cab.

Engine: 57 hp Simca 4-cylinder

Transmission: 4 & 1

Final drive: Through 4 rubber sprockets on 2 tracks

Fuel capacity: 18 gal

Payload capacity: 1000 lb

Overall length: 94 in.

Overall width: 72 in.

Overall height (to top of windshield): 59 in.

Height from ground to hull: $21\frac{1}{2}$ in.

Vehicle weight: 2050 lb

Freeboard when floating empty: 11 in.

Track type: $5\frac{1}{2}$ in. wide rubber and fabric belts with steel crosslinks, each track 27 in. wide

Wheels: 16 wheels, each fitted with 4.80/4.00 x 8 tires

Nominal ground pressure: $\frac{1}{2}$ psi

Ground clearance: $8\frac{3}{4}$ in.

Turning radius: 10 ft

Maximum speed: 25 mph

Cruising speed: 15 mph

Buoyancy: Each 235 lb of load immerses the vehicle 1 in. deeper.

To propel the vehicle on water a light outboard motor must be attached. The motor should not exceed 5 hp.

Bombardier Ski-Doo

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: A light motor toboggan for personnel transport (2-seats) and for hauling very small sledges. Has front-end skis and a single track running beneath the seat for propulsion.

Engine: Two options — single cylinder 4-cycle air-cooled developing 7 hp at 3600 rpm, or single-cylinder 2-stroke giving 8 hp at 4000 rpm

Drive: Roller chain in oil bath and belt and sheaves to give automatic shift

Fuel capacity: 4.8 gal

Fuel consumption: $\frac{1}{2}$ gal/hr

Length: 106 in.

Width: 33 in.

Height (excluding windshield): 32 in.

Vehicle weight: 345 lb

Skis: 2 steerable skis

Track system: Rubber band with steel reinforcing cross-links. Eleven steel wheels with rubber tires and 2 sprockets.

Track size: Bearing area 48 in. long x 15 in. wide

Bearing area: 1200 in.^{2}

Nominal ground pressure: 0.3 psi

Eliason Motor Toboggan

Manufacturer: Four Wheel Drive Auto Co., Ltd., Kitchener, Ontario, Canada

Description: One-man scooter-type vehicle running on 2 skis with a single track for propulsion. It can tow up to 1000 lb of cargo on toboggans (Fig. 18).

Engine: Single cylinder air-cooled, 4-cycle Briggs & Stratton, 8.4 hp at 3600 rpm

Fuel consumption: up to 21 mpg

Length: 7 ft 9 in.

Width: 2 ft 9 in.

Height: 3 ft 0 in.

Vehicle weight: 460 lb

Skis: 2 steerable skis

Track: Single track running between the skis

Maximum speed: 25 mph

Towing capacity: up to 2000 lb on Nansen sledges

Nodwell 3-axle Tracked Carrier Model RN 21

Manufacturer: Robin-Nodwell Mfg. Ltd., Calgary, Alberta, Canada

Description: Light freight or personnel carrier, available with driving cab and flat deck or with fully enclosed cabin. Flexible tracks on pneumatic tires.

Engine: 130 hp Ford 223 $in.^3$ 6-cylinder

Transmission: 4 & 1

Fuel capacity: 24 gal

Payload: 2100 lb

Load area (flat deck model): 6 ft x 6 ft

Width: 6 ft 9 in.

Length: 11 ft 0 in.

Height: 6 ft 10 in.

Vehicle weight: 4800 lb

Tracks: 3-ply 10 in. belts with spring steel crosslinks, track width 28 in.

Track area at zero penetration: 4750 $in.^2$

Ground pressure (loaded): 1.45 psi at zero penetration, 1.16 at 10 in. penetration

Tires: 4.50 x 16, 6-ply, 6 wheels

Ground clearance: 10 in.

Fording depth: 30 in.

Steering: Controlled differential without outer planetaries

Turning radius (inside): 103 in.

Speed: 25 mph

Nodwell 3-axle Tracked Carrier Model RN 50

Manufacturer: Robin-Nodwell Manufacturing Ltd., Calgary, Alberta, Canada

Description: Tracked carrier for transporting personnel or cargo. Flexible tracks on pneumatic tires.

Engine: 130 hp Ford 223 $in.^3$ 6-cylinder

Transmission: 4 & 1

Fuel capacity: 46 gal

Payload: 5000 lb

Load area (flat deck): 7 ft x 9 ft

Width: 8 ft 4 in.

Length: 15 ft 6 in.

Height: 8 ft 0 in.

Vehicle weight: 7700 lb

Tracks: 3-ply 11 in. belts with spring steel crosslinks, track width 32 in.

Track area at zero penetration: 6016 $in.^2$

Ground pressure (loaded): 2.1 psi at zero penetration, 1.65 psi at 10 in. penetration

Tires: 7.50 x 16, 8-ply, 6 wheels

Ground clearance 14 in.

Fording depth: 34 in.

Steering: Controlled differential with outer planetaries

Turning radius (inside): 103 in.

Speed: 12 mph (25 mph available as optional extra)

Nodwell 3-axle Tracked Carrier Model RN 75

Manufacturer: Robin-Nodwell Mfg. Ltd., Calgary, Alberta, Canada

Description: All-purpose carrier, available with flat cargo deck, passenger cabin or special equipment. Flexible tracks running on pneumatic tired wheels.

Engine: 130 hp Ford 223 in.^{3} 6-cylinder

Transmission: 4 & 1

Fuel capacity: 46 gal

Payload: 7500 lb

Load area: 7 ft x 9 ft

Width: 8 ft 11 in.

Length: 15 ft 6 in.

Height: 8 ft 0 in.

Vehicle weight: 9100 lb

Tracks: 3-ply 15 in. belts with spring steel cross links, track width 40 in.

Track area at zero penetration: 7520 in.^{2}

Ground pressure (loaded): 2.2 psi at zero penetration, 1.75 psi at 10 in. penetration

Tires: 7.50 x 20, 12-ply, 6 wheels

Ground clearance: 16 in.

Fording depth: 36 in.

Steering: Controlled differential with outer planetaries

Turning radius (inside): 103 in.

Speed: 12 mph

Nodwell 4-axle Tracked Carrier Model RN 110

Manufacturer: Robin-Nodwell Mfg. Ltd., Calgary, Alberta, Canada

Description: Heavy duty carrier available with flat cargo deck or with special fittings. Flexible tracks running on pneumatic tires (Fig. 22).

Engine: 190 hp Ford 292 in.^{3} V8

Transmission: 4 & 1

Fuel capacity: 46 gal

Payload: 11,000 lb

Load area (flat deck): 7 ft x 12 ft

Width: 8 ft 11 in.

Length: 19 ft 4 in.

Height: 8 ft 0 in.

Vehicle weight: 10,600 lb

Tracks: 4-ply 15 in. belts with spring steel crosslinks, track width 40 in.

Track area at zero penetration: 10,720 in.^{2}

Ground pressure (loaded): 2 psi at zero penetration, 1.68 psi at 10 in. penetration

Tires: 7.50 x 20, 12-ply, 8 wheels

Ground clearance: 16 in.

Fording depth: 36 in.

Steering: Controlled differential with outer planetaries

Speed: 12 mph

Turning radius (inside): 103 in.

Nodwell 4-axle Tracked Carrier Model RN 140

Manufacturer: Robin-Nodwell Mfg. Ltd., Calgary, Alberta, Canada

Description: Heavy cargo carrier employing flexible tracks around pneumatic tired wheels (Fig. 21).

Engine: 190 hp Ford 292 $in.^3$ V8

Transmission: Automatic

Fuel capacity: 46 gal

Payload: 14,000 lb

Load area: 7 x 12 ft

Width: 10 ft 0 in.

Length: 19 ft 6 in.

Height: 8 ft 4 in.

Vehicle weight: 13,200 lb

Tracks: 5-ply, 18 in. rubber belts with spring steel crosslinks, track width 48 in.

Track area at zero penetration: 14,000 $in.^2$

Ground pressure (loaded): 1.95 psi at zero penetration, 1.65 psi at 10 in. penetration

Tires: 7.50 x 20, 12-ply, 8 wheels

Ground clearance: 16 in.

Fording depth: 36 in.

Steering: Controlled differential with outer planetaries

Turning radius (inside): 112 in.

Speed: 12 mph

Nodwell 8-axle, 4-track Transporter Model RN 200

Manufacturer: Robin-Nodwell Mfg. Ltd., Calgary, Alberta, Canada

Description: Heavy articulated flat-deck cargo carrier. Two 4-axle units are connected by fifth wheel arrangements to the cargo deck and are powered independently by 2 engines (Fig. 24).

Engines: Ford 292 $in.^3$ V8 (2)

Transmission: Automatic (2)

Fuel capacity: 168 gal

Payload: 20,000 lb

Load area: 8 x 23 ft

Width: 10 ft 0 in.

Length: 39 ft 0 in.

Height: 8 ft 4 in.

Vehicle weight: 36,000 lb

Tracks: 5-ply, 18 in. belts with spring steel crosslinks, track width 48 in.

Track area at zero penetration: 28,000 $in.^2$

Ground pressure (loaded): 2 psi at zero penetration, 1.7 psi at 10 in. penetration

Tires: 7.50 x 20, 12-ply, 16 wheels

Ground clearance: 16 in.

Fording depth: 36 in.

Steering: Hydraulic power

Turning radius (inside): 25 ft

Speed: 12 mph

RUSSIAN VEHICLES

Kharkovchanka (Bogatyr)

Manufacturer: Kharkov tractor works, U.S.S.R.

Description: Expedition tractor equipped for living and scientific observation, with additional drawbar pull of about 15,000 lb (Fig. 14). Range shift steering.

Engine: 12-cylinder diesel developing 520 hp basic and 1000 hp supercharged (V-12)

Transmission: 5-speed Fuel capacity: 700 gal

Length: 28 ft

Width: 13 ft

Height: 13 ft

Vehicle weight: 78,000 lb

Tracks: 2 tracks, conventional type with stiff track plates. Full depth bogies. Track width 30 in. to 40 in. (40 in. track subject to rapid wear)

Ground pressure: 4 psi

Maximum speed: 28 mph claimed, 15 mph U. S. estimate (Ordnance)

Towing capacity: Reported variously as 78 tons planned and 150 tons actual

Altitude toleration: Can operate at 13,000 ft

Lowest operating temperature: -94F

Special features: Large insulated cabins (insulated for 180 F temperature differential) containing eight compartments: driving cab, workroom, galley, service compartments, toilet, drying room, lobby

Pingvin

Manufacturer: U.S.S.R.

Description: Russian cross-country vehicle for reconnaissance and personnel carrying. Conventional Russian military-type track with full-depth bogies. Amphibious.

Engine: Diesel, 240 hp, supercharged

Load capacity: 5000 lb

Length overall: 265 in.

Width overall: 124 in.

Height overall: 96 in.

Weight (empty): 24,000 lb

Track width: 26 in.

Maximum speed: 25 mph (estimated) on land, 5 mph (estimated) on water

Cruising range: 400 miles

<u>GAZ-47 cross-country vehicle</u>

Manufacturer: Gorky Motor Works, USSR (1947)

Description: Cross-country vehicle for personnel and light cargo.

Engine: 80 hp, unsupercharged

Payload: 6 men

Track width: 14 in.

Tract type: Flexible track running around full-depth wheels (5 each side) and driven from a front sprocket

<u>S-80 Tractor ("Stalinet")</u>

Manufacturer: USSR

Description: Mass-produced engineer tractor.

Engine: 80 hp, unsupercharged

Track width: 20 in.

<u>S-100A and S-100AB tractors</u>

Manufacturer: USSR

Description: Modifications of the S-80 tractor. "A" designates Antarctic modification, "B" indicates further modification for boggy ground.

Engine: 100 hp, supercharged

Track width: 30 in. (S-100A); 40 in. (S-100AB)

<u>"Heavy-duty tractor"</u>

Manufacturer: USSR

Description: Tractors used for carrying and hauling heavy loads in Antarctica.

Engine: 400 hp, unsupercharged

Track width: 20 in.

<u>"Modernized heavy-duty tractor"</u>

Manufacturer: USSR

Description: Modification of the "heavy duty tractor," with wider tracks, supercharged engine, and improved cabin.

Engine: 400 hp, supercharged

Track width: 30 in.

SWEDISH VEHICLES

<u>Snow-Trac</u> Model SR2

Manufacturer: AB Westeråsmaskiner, Morgongåva &Stockholm, Sweden

Description: Light personnel and cargo carrier running on flexible tracks (Fig. 19).

Engine: 4-cylinder air-cooled Volkswagen (36 hp)

Transmission: 4 & 1

Fuel capacity: 105 gal

Load capacity: 1100 lb on vehicle, 1100 lb on sled

Length: 144 in.

Width: 75 in.

Height: 43 in. with windshield down, 71 in. with windshield up

Weight: 2200 lb empty

Track system: Reinforced rubber belts running around spring bogies. Front sprocket drive

Track bearing area: 3450 $in.^2$

Nominal ground pressure: 0.75 psi (light load), 1.0 psi (full load)

Ground clearance: 12 in.

Turning radius: 8 ft

Maximum speed: 13 mph

BRITISH VEHICLES

<u>Ferguson farm tractor</u> Model TE20

Manufacturer: Massey Ferguson Co., Coventry, England

Description: Light farm tractor fitted with bombardier-type track (rubber belts with steel cross links). A half-track version has been used on shallow seasonal snow cover, but for true oversnow work larger front wheels and a complete track were fitted (Fig. 25).

Engine: 4-cylinder gasoline, 28 bhp at 2000 rpm

Fuel capacity: 11 gal

Length: 10 ft

Width: 6 ft 1 in.

Height: 4 ft 4 in.

Vehicle weight: 3370 lb (with full tracks)

Nominal ground pressure: 1.3 psi

Turning radius: 20 ft

Maximum speed (on snow): 10 mph

APPENDIX B. SLEDS AND TRAILERS

M14 1-ton cargo sled

M53 $2\frac{1}{2}$-ton reconnaissance sled

Norwegian cargo sled

Otaco 10-ton cargo sled

Otaco 20-ton cargo sled

Off-road cargo trailer (10-ton Sno-Trailer)

T3 Rolling liquid transporter

Rolli-Trailer

Bombardier tracked trailer

M14 1-ton cargo sled (Fig. 32a)

Length: 115.75 in. excluding drawbar

Width: 50.25 in.

Height: 18.375 in.

Weight (empty): 610 lb

Payload: 2000 lb

(M52 1-ton reconnaissance sled is similar to the M14)

M53 2½-ton reconnaissance sled

Length (deck): 156 in.

Width (deck): 72 in.

Weight (empty): 700 lb

Payload: 5000 lb

Runner width: 18 in.

Contact area: 4300 in.^{2}

Nominal ground pressure: 1.3 psi loaded

(There is also an M53 farm-type bobsled with 2½-ton capacity)

Norwegian cargo sled (Fig. 32c)

Manufacturer: A/S Kolbjørn Knutsen Co., Oslo, Norway

Description: Light-weight hickory sled with steel-sheathed runners

Length: 13 ft

Width: 4 ft 3 in.

Height: 1 ft 2 in.

Weight (empty): 400 lb

Payload: 6000 lb

Otaco 10-ton cargo sled (Fig. 33)

Length: 268 in. excluding drawbar, 234 in. deck length

Width: 102 in. overall, 88 in. deck

Height: 35 in. to deck, 87 in. to top of stakes

Weight (empty): 9000 lb

Payload: 20,000 lb

Nominal contact area: 5184 in.^{2}

Nominal ground pressure: 5.6 psi fully loaded

Otaco 20-ton sled (Fig. 33)

Length: 288 in. overall

Width: 144 in. overall

Height: 32 in. to deck

Weight (empty): 20,000 lb

Payload: 40,000 lb

Nominal contact area: 8,496 $in.^2$

Nominal ground pressure: 7.1 psi fully loaded

Off-road cargo trailer (10-ton Sno-Trailer)

Length: 35 ft 6 in. without drawbar, 39 ft 6 in. overall

Width: 12 ft 0 in. overall

Height: 10 ft 0 in. overall

Weight (empty): 18,000 lb

Payload: 20,000 lb

Wheelbase: 25 ft 6 in.

Track: 8 ft 9 in.

Inflation pressure: 15-25 psi or 5-10 psi

Tires: 120 OD x 48W x 68 Firestone or 118 OD x 44½W x 45 Goodyear

Turning radius: 50 ft

Ground clearance: 2 ft 0 in.

Bed height: 3 ft 5 in.

Cargo area: 190 ft^2

Rolling liquid transporter (wheel type T-3)

Length: 140 in. overall, 64 in. excluding drawbar

Width: 98 in.

Height: 64 in.

Towbar height: 35 in.

Weight (empty): 2240 lb

Capacity: 1000 gal

Gross weight with gasoline: 8540 lb

Fuel cell wheels: 64 x 42 x 18 in.; 4-ply

Pressure: 3 - 15 psi

Ground clearance: 28 in.

Maximum towed speed: 25 mph

Rolli-Trailer

Manufacturer: Ordnance

Description: Combination POL and dry cargo carrier made by joining two Rolling liquid transporters with a steel frame and cargo deck (Fig. 37).

Length overall: 336 in.

Width overall: 104 in.

Height overall: 102 in.

Towbar height: 35 in.

Vehicle weight (empty): 6750 lb

Gross weight with gasoline only: 19,350 lb

Gross weight with gasoline and full cargo: 25,350 lb

Dry cargo capacity: 6000 lb

Fuel capacity: 2000 gal

Wheelbase: 196 in.

Fuel cell wheels: 4 wheels, each 64 x 42 x 18 in.

Pressure: 3 - 15 psi

Ground clearance: 27 in.

Bombardier tracked trailer

Manufacturer: Bombardier Snowmobile Ltd., Valcourt, Quebec, Canada

Description: Small tracked trailer

Gross weight: 4000 lb

Payload: 3000 lb

Wheels: Pneumatic-tired, 3 duals each side

Tracks: Rubber belts with steel crosslinks

Nominal ground pressure: 1 - 2 psi

APPENDIX C. POTENTIAL OVERSNOW VEHICLES — AIR CUSHION VEHICLES

(The machines listed here have been selected from the many ACV's currently under development as coming closest to oversnow requirements)

<u>U.S.</u>

Bertelsen Aeromobile A-200-1

NRA GEM No. 3

Curtiss-Wright Air-Car, Model 2500

Aeronutronic experimental ACV

<u>British</u>

Britten-Norman Cushioncraft CC-2

Folland GERM

Vickers-Armstrong VA-2

Westland (Saunders-Roe) SR-N1 Hovercraft

U. S. ACV'S

Bertelsen Aeromobile A-200-1

Manufacturer: Bertelsen Manufacturing Co., Neponset, Illinois

Description: Amphibious air cushion passenger vehicle. Peripheral air curtain.

Length: 16 ft

Width: 8 ft

Height: 5 ft 6 in.

Vehicle weight: 1700 lb

Loaded weight: 2700 lb

Fuel capacity: 17 gal

Seating capacity: 4

Engine: 6-cylinder air-cooled Franklin, 178 hp

Fan: 16-blade adjustable pitch mounted horizontally amidships

Maximum hovering height: 12 in.

Maximum speed: 60 mph

Cruising speed: 45 mph

Maximum range: 109 miles

Propulsion, altitude control, braking: All by thrust diversion using adjustable peripheral flaps

Maximum gradient: 20% short gradients, 15% long gradients

NRA GEM No. 3

Manufacturer: National Research Associates, Laurel, Maryland

Description: Turbine-powered air cushion vehicle for research purposes.

Length: 22 ft

Width: 12 ft

Weight: 1835 lb loaded

Engine: Two 80 shp Solar Titan shaft-turbine engines

Fan: Two 38-in. diam 12-blade ducted fans mounted vertically. Fans feed air through ducts to a 4 in. wide peripheral slot around the base.

Hovering height: 12-18 in.

Maximum speed: 30 mph

Propulsion and directional control: Deflection of the air curtain by vanes

Altitude control: Pressure relief valves

Curtiss-Wright Air-Car Model 2500

Manufacturer: Curtiss-Wright, Woodridge, N. J.

Description: Passenger vehicle,

Length: 21 ft

Width: 8 ft

Height: 6 ft

Weight: 2700 lb (vehicle + fuel)

Lift capacity: 3500 lb

Fuel capacity: 2 x 20 gal

Seating capacity: 4

Engine: Two Lycoming, each 180 hp air-cooled

Hovering height: 10 in.

Speed: 38 mph cruise, 60 mph maximum

Air cushion pressure: 0.1 psi

Maximum gradient: 6%

Maximum operating altitude: 7000 ft

Aeronutronic experimental ACV

Manufacturer: Aeronutronic Division of Ford Motor Co., Newport Beach, Calif.

Description: Amphibious fully skirted ACV for personnel or cargo carrying.

Length: 21 ft

Width: 8 ft

Cargo space: 4 x 13 ft

Gross weight: 7000 lb

Payload: 2000 lb (full range), 4000 lb (short range)

Hovering height: 2 to 3 ft

Speed: 40 mph

Maximum gradient: 20%

Range: 100 miles

Propulsion, control, braking: Venting air curtain through peripheral vanes

BRITISH ACV'S

Britten-Norman CC-2 Cushioncraft

Manufacturer: Britten-Norman Ltd., Bembridge Airport, Isle of Wight, England

Description: "Second generation" amphibious air cushion vehicle for carrying passengers or light cargo.

Length: 27 ft

Width: 17 ft

Height: 8 ft 6 in.

Weight (empty): 3100 lb

Normal loaded weight: 5500 lb

Overload maximum weight: 7000 lb

Passenger capacity: 10

Engine: Liquid-cooled 8-cylinder Rolls-Royce, 6230 cm^3

Fan: Two horizontally-mounted fans

Maximum hover height: 2 ft

Maximum speed (at 5500 lb): 55 mph

Maximum range (at 5500 lb): 500 miles

Folland GERM

Manufacturer: Folland Aircraft Ltd. (member of Hawker Siddeley Group), Southampton, Hampshire, England

Description: The GERM is an experimental vehicle which is fitted with a pair of wheels to facilitate maneuvering and directional control. The wheels carry a small proportion (about 10%) of the vehicle's weight. An oversnow machine might similarly be fitted with skis for stability.

Length: 16 ft 6 in.

Width: 8 ft (excluding wheels)

Loaded weight: 2200 lb

Engine: Two Coventry Climax 4-cylinder engines, one driving a pair of axial-flow fans to feed the air cushion, and one driving a ducted fan for propulsion

Vickers-Armstrong VA-2

Manufacturer: Vickers-Armstrong Ltd., Swindon, Wilts., England

Description: Utility vehicle for carrying passengers or light cargo over water or soft terrain.

Length: 28 ft 4 in.

Width: 14 ft 10 in.

Height: 10 ft 4 in.

Payload: 1000 lb

Loaded weight: 6000 lb

Engine: Three light aircraft piston engines, two for lift and one for propulsion

Hover height: 8½ in.

Cruising speed: 46 mph

Westland (Saunders-Roe) SR-N1 Hovercraft

Manufacturer: Saunders-Roe Division of Westland Aircraft Ltd., Yeovil, Somerset, England

Description: The SR-N1 is a successful development machine. Suggested specifications for an oversnow version were supplied to USA CRREL by the developers; these are given below, with specifications of the existing SR-N1 in parentheses.

Length: - (30 ft)

Width: - (24 ft)

Weight loaded: 18,000 lb (13,000 lb)

Overload weight: 22,400 lb maximum

Normal payload: 4500 lb or 25 passengers

Total payload: 9000 lb in the overload condition

Operating hover height: 2 ft at maximum continuous power (13 in.)

Maximum hover height: 3 ft at not more than 60% maximum speed at 1 hr engine rating

Forward speed: 70 mph maximum (52 mph)

Reverse speed: 30 mph maximum

Range: 230 miles with normal payload at normal operating height at 70 mph

Tolerable side wind: Stationary hovering in 20-mph side wind

Maximum gradient: 14% starting from rest, with zero wind

Negotiable sideslope: Able to traverse 5% slope at 1 hr engine rating